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THESIS

SMART ANTENNA APPLICATION IN DS-CDMA MOBILE COMMUNICATION SYSTEM

by

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We further apply tapped-delay line (transversal filter) to each antenna element channel, to allow frequency dependent amplitude and phase adjustment for broadband signals. The performance of a DS-CDMA cellular system with a mobile terminal equipped with a linear array and a tapped-delay line is analyzed. It has been demonstrated that the optimization process has been extremely computationally expensive and hence minimum taps should be used for practical consideration. The results illustrated that, in general, for a 2-element linear array system, a 3-tap delay line would be sufficient to equalize the broadband signal while providing a similar performance level to that of a narrow-band adaptive array system. In the case of a 3-element linear array system, a 2-tap delay line would suffice.

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SMART ANTENNA APPLICATION IN DS-CDMA MOBILE COMMUNICATION SYSTEM

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EXECUTIVE SUMMARY

The third-generation (3G) cellular system employs Direct Sequence Code Division Multiple Access (DS-CDMA) that allows simultaneous sharing of limited available bandwidth. However, the DS-CDMA scheme limits the system's capacity and performance because it causes inter-cell co-channel interference and intra-cell interference. In order to meet the growing demand of high data-rate services, various techniques were explored to increase the system's capacity.

This thesis analyses the performance of the base-station to the mobile channel (forward channel) of a DS-CDMA system in a slow, flat Rayleigh fading and log-normal shadowing environment. The forward channel is being studied because most data services are asymmetric, with the downstream requiring a higher data rate. We explore the use of an adaptive linear-array antenna at the mobile terminal to suppress the interferers. This is achieved by steering an antenna null toward the interferer while forming an antenna beam toward the desired signal continuously with time. This would minimize the Interference-to-Signal Ratio, which improves the system's performance and the system's capacity.

Four performance boundaries of the DS-CDMA mobile communication system with an adaptive array were established. The worst-case performance of the system was compared with a DS-CDMA system without the smart antenna application. With the Monte Carlo simulation, the results showed that the system's capacity and performance could be greatly improved with a smart antenna application. At BER of 10^{-3} or less, with a 2-element or a 3-element linear array, an impressive capacity gain of 600% or 900% can be achieved, respectively, in the worst-case scenario.

The thesis further explores the use of a wideband smart antenna (Tapped-Delay Line) system. In the case of a 2-element and a 3-element linear array, we demonstrate that 3- and 2-tap delay lines are sufficient to equalize and to compensate for the frequency variation of a 4% bandwidth broadband signal.

The application of the smart antenna technology at the mobile terminal for the third-generation DS-CDMA cellular system can be extended to the military mobile communication systems. By doing so, the military mobile communication system will be more robust since the mobile terminals are able to suppress possible interference by steering the antenna null toward them. Similarly, the military mobile communication system's capacity and maximum data rates can also be improved using the smart antenna.

I   INTRODUCTION

The third-generation (3G) cellular system employs a multiple-access technique known as Direct Sequence Code Division Multiple Access (DS-CDMA. Simultaneous multiple-user access in such a system provides efficient use of the limited bandwidth. However, the DS-CDMA scheme used in the cellular system also creates problems in the network, such as inter-cell co-channel interference and intra-cell interference. This thesis analyzes the performance of the forward channel (base-station to mobile) of a DS-CDMA system in a slow, flat Rayleigh fading and log-normal shadowing environment. Generally, data services are symmetric, with the downstream requiring a high data rate. The forward channel will be used to download data from sources, such as the Internet, at a high data rate from the base-station to the mobile terminal.

With the ever-increasing demand to accommodate more users and higher data-rate services within a limited available frequency spectrum, many researchers have explored new options to improve the system's capacity and performance. One of the most promising techniques for increasing cellular system capacity is the use of smart antennas. A mobile communication system often encounters co-channel interferers who occupy the same channel as the desired user. This limits the system's performance and capacity. The most modern method of using dual diversity with Maximum Ratio Combining at the receiver cannot reduce the high interference. This is true because the strategy of selecting the strongest signal or extracting the maximum signal power from the antennas is not appropriate. It will enhance the interferer signal rather than the desired signal. However, if we could estimate the direction of arrival (DoA) of the interferers and the desired signal, we could then use an adaptive antenna array to suppress the interference by steering a null toward the interferer and forming a beam toward the desired signal continuously with time. Therefore, the dynamic system performance can be improved.

Most of the performance analyses of the DS-CDMA cellular system have focused on the reverse channel, such as in [6], even with the use of a smart antenna. However, most of these performance analyses have only incorporated a subset of the channel

effects (fading and shadowing) and the benefits of forward error correction with soft decision decoding.

In this thesis, we implemented an equally spaced linear antenna array with a different number of elements at the mobile terminal. We analyzed the performance of a randomly positioned mobile terminal with a randomly orientated adaptive antenna array in a multi-cell DS-CDMA network and established four performance boundaries.

We select the tighter optimized array antenna boundary as our performance reference, as it is more conservative and represents the worst-case situation. We then combine the conservative optimized 2-, 3- and 4-element array antenna with the DS-CDMA forward-channel received signal model developed in [4]. The model in [4], which originally incorporated both log-normal shadowing and Rayleigh slow flat fading, now includes the effect of the smart antenna. We further combined the benefit of forward error correction with soft decision decoding to obtain the new system model. Finally we compared the capacity and performance of different cellular systems under a range of shadowing conditions, with and without antenna sectoring at the base-station and for various user capacities using a Monte Carlo simulation.

All the previous analyses assumed that the system is a narrowband system. In [6] the smart-antenna analysis was assumed to have an ideal wideband antenna. The presence of a single, complex, adaptive weight in each element channel of an adaptive array is sufficient for processing narrowband signals. However, processing broadband signals, such as the forward channel of a 3G DS-CDMA network, requires that a tapped-delay line (transversal filter) processing be employed in each element channel. In a practical implementation, each channel is slightly different electrically. It will lead to channel mismatching, which could significantly alter the frequency response characteristics from channel to channel. This may severely degrade the antenna array performance. The tapped-delay line permits frequency-dependent amplitude and phase adjustments to be made, to equalize the frequency-varying effect on the antenna when receiving a

broadband signal. We also analyzed the performance of a DS-CDMA cellular system with mobile terminal equipped with a linear array and tapped-delay line.

Now, there is a trend to adopt commercial off-the-shelves products for military applications because this approach can be more cost effective. With slight modification of the commercial mobile communication system, the modified system can be deployed for military applications. Hence the performance analysis in the application of the smart antenna technology at the mobile terminal for the third-generation DS-CDMA cellular system can be valuable for military use.

In Chapter II, we will discuss the co-channel interference of a DS-CDMA system and various methods to minimize the interference problem. And in Chapter III, we will introduce the characteristics and constraints of an equally spaced linear adaptive array system. This adaptive array will be used in our DS-CDMA system for analyzes. The forward channel propagation model for DS-CDMA system will be introduced in Chapter IV. Chapters V and VI discuss the performance of an adaptive antenna system in a narrow-band and a wide-band DS-CDMA forward channel respectively.

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II   SMART ANTENNA APPLICATION IN MOBILE COMMUNICATION

In this chapter, we will discuss the main constraint of a DS-CDMA mobile communication system and different methods to improve the system capacity and performance. The main constraint of the DS-CDMA network is the co-channel interference. Application of cell sectoring and smart antenna are the common methods used to combat the co-channel interference.

A.   CO-CHANNEL INTERFERENCE

In the CDMA cellular mobile communication network in which the radio-frequency spectrum is shared, the multipath signal fading environment and the multiple co-channel interferers limits the system's performance. With the co-channel interference as the major limiting factor for performance [7], the CDMA based network is hence an interference-limited system. Consequently in order to improve the system's performance and capacity, minimizing the system interference would be most effective. However, unlike thermal noise, which can be overcome by increasing the signal power, co-channel interference cannot be overcome by increasing the signal power. Doing so increases interference to the neighboring co-channel cells.

In a multi-cell cluster, such as a TDMA IS-54/GSM system, interference can be suppressed by increasing the physical separation of co-channel cells until a sufficient isolation is achieved due to the propagation loss. This can be achieved by increasing the cluster size N. The Signal-to-Interference (SIR) Ratio, is defined in [7] as

$$\text{SIR} = \frac{\left(\sqrt{3N}\right)^n}{i_o} \tag{2.1}$$

where i_o is the number of interferer and n is the path loss exponent.

However in the case of a CDMA network in which the whole frequency spectrum is shared and reused by all first-tier neighboring cells, the distance between the base-station to any co-channel base-station is fixed at $\sqrt{3}$ R where R is the radius of the hexagonal cell (Figure 2.1). Thus in the single-cell CDMA network, we do not have the freedom to vary the cluster size N to reduce the co-channel interference.
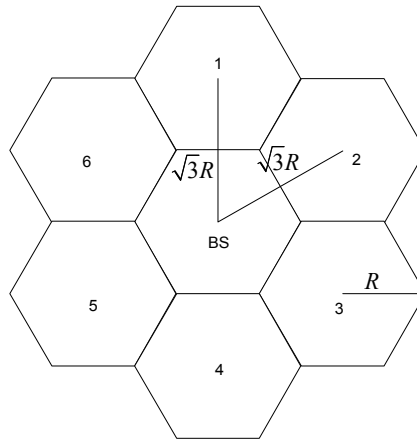
Figure 2.1　　Geometry of a Cellular CDMA Mobile Communication Network

Another method to reduce the co-channel interference must be explored in order to improve the system performance. Two common methods to combat the co-channel interference are by sectoring and by using smart antenna technology.

B.   SECTORING

The co-channel interference in a cellular mobile communication system can be reduced by replacing the omni-directional antenna at the base-station with several directional antennas. The use of a directional antenna limits the number co-channel interferers seen by any receiver within the cell. This is true because each directional antenna only radiates within a desired sector. This technique is called sectoring. The scale of the reduction of co-channel interference depends on the number of sectors used. A cell is commonly partitioned into three 120-degree or six 60-degree sectors, as shown in

Figure 2.2. In the case with users evenly distributed within all cells, the amount of co-channel interference is reduced to 1/3 or 1/6 of the omni-directional value if 120-degree or 60-degree sectoring is used respectively.
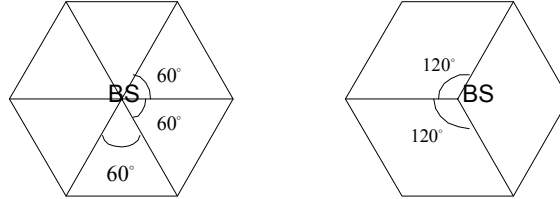
Figure 2.2   60° and 120° Cell Sectoring

Many papers such as [4], which evaluated the forward channel performance in the fading environment, evaluate and present the improved performance with the use of 6 and 3 sectors of 60° and 120° sectors, respectively, in a DS-CDMA cellular system operating in a channel with Rayleigh fading and log-normal shadowing.
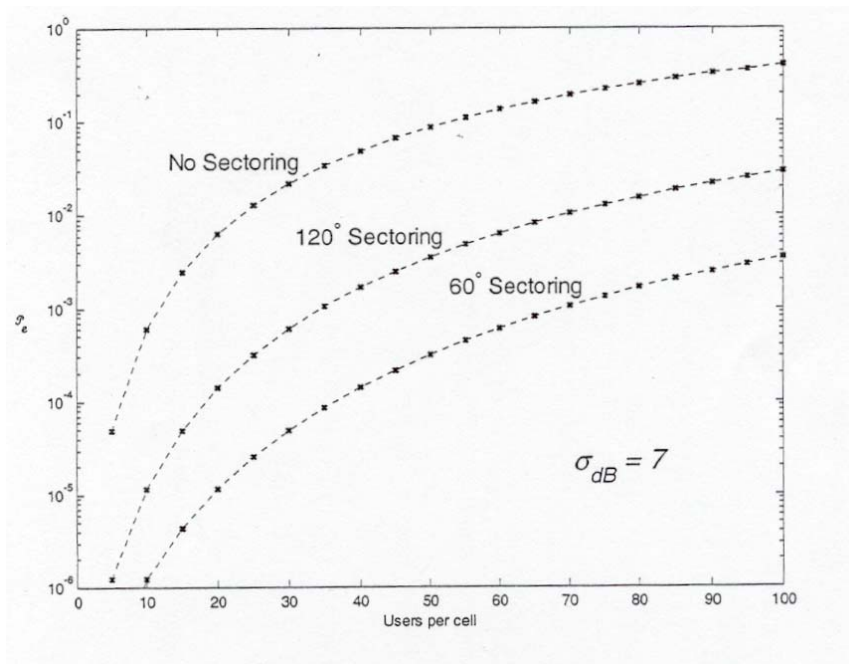
Figure 2.3   Probability of Bit Error for DS-CDMA Using Sectoring (σ_{dB} = 7) with an SNR per Bit of 15 dB with Rate 1/2 Convolution Encoder with v=8. (From:[4])

C.   SMART ANTENNA

A smart antenna system, which is an antenna array arranged in a certain distributed configuration with a specialized signal processor, can be deployed in the CDMA mobile communication system to improve the system's performance and capacity significantly by minimizing undesired co-channel interference. Most of the smart antenna systems can form beams directed to a desired signal and form nulls toward undesired interferer such as a co-channel base-station. This will enhance the signal-to-interference (SIR) ratio because the received desired signal strength is maximized and the undesired interference is minimized. Other benefits of a smart antenna include:

- increase in range or coverage arising from an increased signal strength due to array gain,
- increase capacity arising in interference rejection,
- reject multi-path interference arising from inherent spatial diversity of the array,
- reducing expense arising from lower transmission powers to the intended user only.

A smart antenna system is commonly classified into three categories: switched beam antennas, dynamic phased arrays and adaptive antennas. Although a multiple antenna system is also commonly used at the receiver for L-fold diversity, which could mitigate the harmful effects of fading by reducing the signal fluctuations when the signal is sufficiently de-correlated, the multiple antennas cannot distinguish a co-channel signal. This method of extracting the maximum signal power from the antennas is not appropriate because it also enhances the co-channel interference together with the desired signal.

A switched-beam antenna system consists of many highly directive, pre-defined fixed beams formed with an antenna array. The system usually detects the maximum received signal strength from the antenna beams and chooses to transmit the output signal from one of the selected beams that gives the best performance. In some sense, a

switched beam antenna system is very much like an extension of a sectoring directional antenna with multiple sub-sectors. Since the direction of the arrival information of the desired signal is not explored, the desired signal may not fall onto the maximum of the chosen beam because these beams are fixed. Hence switched beam antennas may not provide the optimum SIR. In fact, in cases where a strong interfering signal is at or near the center of the chosen beam, while the desired user is away from the center of the chosen beam, the interfering signal can be enhanced far more than the desired signal, which results in very poor SIR.

Dynamic phased arrays use the direction of arrival (DoA) information from the desired signal and steer a beam maximum toward the desired signal direction. This method when compared to switch-beam antenna, is far more superior in performance because it tracks the desired user DoA continuously, using a tracking algorithm to steer the beam toward the desired user. The tracking of the DoA enables the system to offer optimal gain for the desired signal, while simultaneously minimizing the reception of the interfering signal by directing the nulls to the interferer's direction. Thus excellent SIR can be achieved.

In the adaptive array, the weights are continuously adjusted to maximize the signal-to-interference-plus-noise ratio (SINR) and to provide the maximum discrimination against undesired interfering signals. If the interferer is absent and if only noise is present, the adaptive antennas maximize the signal-to-noise ratio (SNR) and thus behave as a Maximal Ratio Combiner (MRC). With the use of various signal-processing algorithms at the receiver-adaptive antenna array system, this system can distinguish between the desired signal and the interfering signals, and can then calculate their direction of arrival continuously. This is done to minimize interference dynamically by steering the nulls patterns toward these undesired sources and to form the maximum gain pattern toward desired signal. Such algorithms are usually implemented by digital signal processing software, which is relatively easy to implement and to enhance. By using other algorithms for branch diversity techniques, the adaptive antenna array system can process and can resolve separate multi-path signals, which can be combined with the

adaptive antenna system to maximize the SINR or SIR.
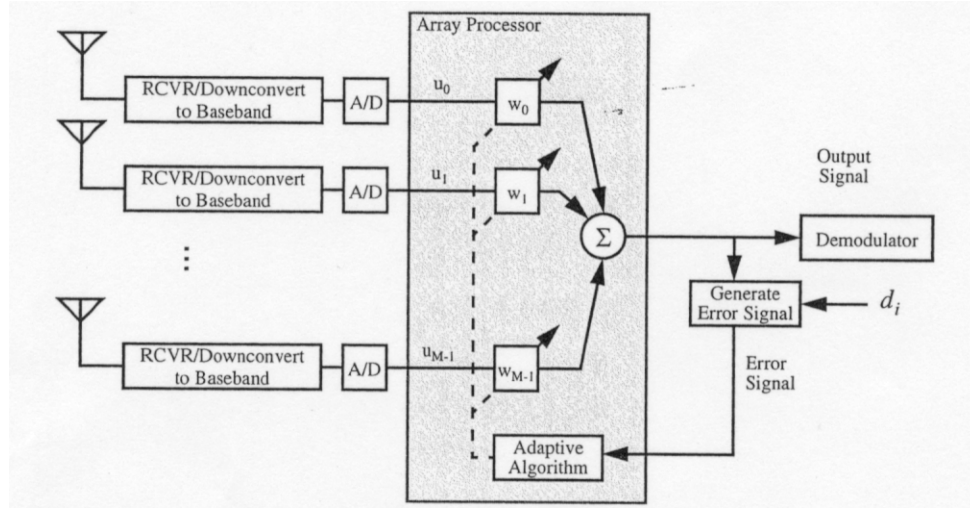
Figure 2.4   Block Diagram of an Adaptive Antenna System (from [5]).

An adaptive antenna array system may consist of N number of spatially distributed antennas with an adaptive signal processor that generates the weight vectors for optimum combining of the antenna array output. This can also be regarded as an N-branch diversity scheme, providing more than the two diversity branches commonly used. The received RF signals from the N-antenna elements are coherently down-converted to a baseband/IF frequency, sufficiently low so that the adaptive array processor can effectively digitalize the signals. The processor processes each digitized input channel by multiplying the adjusted complex weights of each branch to form the beam and the nulls. This results in the beam and null steering, which can be viewed as a spatial filter having a pass and stop band created for the direction of the desired signal and interference respectively.   In general, with N-antenna elements in the adaptive array system, generating (N-1) nulls in the array system radiation pattern toward (N-1) interferer directions is possible. This will reduce the total interferer signal significantly, thus reducing the interferer-to-signal ratio. By reducing the interference in the interference limited system, performance and capacity can be improved.

D. ADAPTIVE ANTENNA ARRAYS APPLICATION IN THE FORWARD CHANNEL

Unlike the base-station, where the physical space is the lesser of a constraint, implementing a larger number of antenna elements with a large signal processor is possible. However the mobile units do not have the luxury of the physical space of the base-station. In today's design of a mobile unit, reducing the physical size and weight is always a prime consideration. Implementing a large number of antenna elements on the mobile unit is not possible. In this thesis, we focus on the performance analysis with the use of adaptive 2-, 3- and 4-element linear array system at the mobile user in the forward channel, because they are likely to fit into a mobile terminal in a future communication system.

For a 4-element (N=4) linear array system at the mobile in a CDMA mobile communication network, the adaptive array processor at the mobile could form a beam toward the desired base-station and up to 3 nulls toward the 3 co-channel interferer (first-tier base-station). Such an adaptive antenna system usually performs null steering first, which minimizes the signal-to-interference ratio (SINR) by suppressing as many interferers as possible so that the desired signal is least distorted. Then the system will use the remaining degrees of freedom to steer the desired beam toward the desired signal direction of arrival to maximize the signal-to-noise ratio (SNR). With this strategy, the system can improve the SINR for the mobile user maximally.

In this chapter, we have illustrated needs to combat the co-channel interference of a DS-CDMA mobile communication system. With the application of the smart antenna, we could maximize the SINR of the system. In the next chapter, we will discuss the characteristics and constraints of an equally spaced linear adaptive array for our application.

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III   LINEAR ADAPTIVE ANTENNA ARRAY

As mentioned in the last chapter, a smart antenna system such as an adaptive antenna array can be applied to a CDMA mobile communication system to maximize the SINR of the system. This is accomplished by maximizing the suppression of the interferers with null steering, and maximizing the SNR by beam steering toward the desired signal. The elements of the adaptive antenna array can be arranged in different configurations such as circular, linear equally spaced, triangular etc. This chapter presents an equally spaced linear adaptive array system.
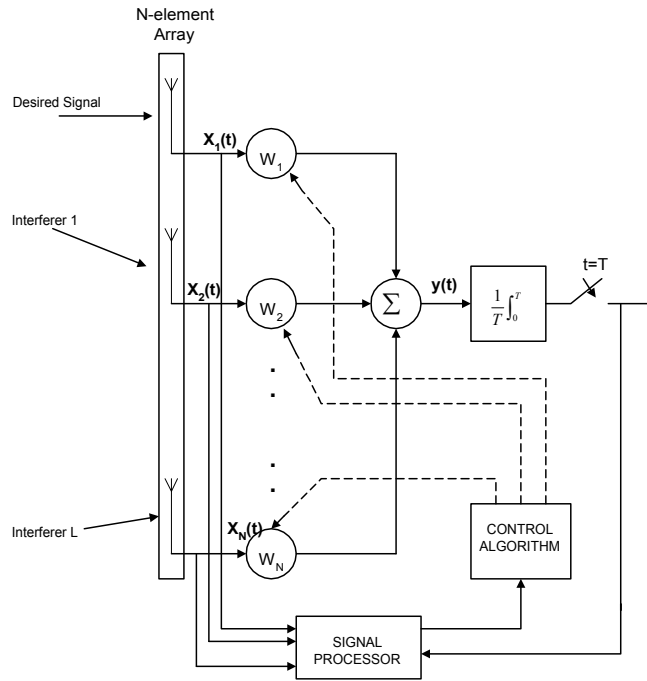
Figure 3.1   Adaptive Antenna Array Systems

Figure 3.1 shows an adaptive antenna array having N elements with L interferers. Let $x_k(t)$ be the received signal at the k-th antenna element output.

$$x_k(t) = s_k(t) + n_k(t) , \ \ k = 1, 2, 3, ... N \tag{3.1}$$

where $s_k(t)$ is the complex signal envelope of the signal and $n_k(t)$ is the noise

received by the k-th antenna element. Letting λ be the wavelength, d be the element spacing, and θ be the incident angle with respect to bore sight, we have

$$s_k(t) = s(t)\, e^{i\frac{2\pi(k-1)d}{\lambda}\sin\theta} \qquad\qquad k = 1,\ 2,\ ...,\ N \qquad\qquad (3.2)$$

The array output signal $y(t)$ is the weighted sum of all $x_k(t)$.

$$y(t) = \sum_{k=1}^{N} w_k x_k(t) = W^T X = X^T W.$$

(3.3)

$$W = \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ w_N \end{bmatrix}, \qquad X = \begin{bmatrix} x_1(t) \\ x_2(t) \\ . \\ . \\ x_N(t) \end{bmatrix}.$$

The adaptive array system continuously adjusts the weights vector **W** by the optimum control algorithm with criterion such as Minimum Mean Square Error (MMSE) [5].

A.   OPTIMAL WEIGHTS

In this thesis we intend to minimize the ISR as our algorithm to compute the optimal weight for the adaptive antenna system. We assume a linear array with 2-, 3- or 4-elements and with element spacing d. To illustrate, we use the case of a 4-element array. The amplitudes are A_1, A_2, A_3 and A_4, and the phases are ψ_1 and ψ_2, ψ_3 and ψ_4. The far-field antenna factor F_{array} is calculated to be in the horizontal plane, hence the angle ϕ denotes the azimuth direction (the angle of azimuth).

$$F_{\text{array}} = A_1 e^{i\psi_1} + A_2 e^{i\psi_2} e^{-i2\pi\frac{d}{\lambda}\sin\phi} + A_3 e^{i\psi_3} e^{-i2\pi\frac{2d}{\lambda}\sin\phi} + A_4 e^{i\psi_4} e^{-i2\pi\frac{3d}{\lambda}\sin\phi}. \qquad (3.4)$$

Let the operating frequency be 2 GHz and the antenna element spacing d of $\lambda/2$, we then normalize the total power (gain) to be equal to 1 by using a relationship of $A_1{}^2 + A_2{}^2 + A_3{}^2 + A_4{}^2 = 1$. We can generate any far field antenna factor in any of the 360-degree azimuth. Figure 3.2 shows the antenna factors of a 4-element antenna array with various phase shifts. We can see that the antenna factor changes significantly over 180 degrees phase shift.

Figure 3.2   4-Element Antenna Array Patterns

The directions of arrival (DoA) of the desired signal ϕ_b (base-station) and the interference signals ($\phi_{i1}, \phi_{i2}, \phi_{i3}$) can be estimated. With these DoA estimated, if we take the desired base-station signal as a reference, the complex gains of the array in the
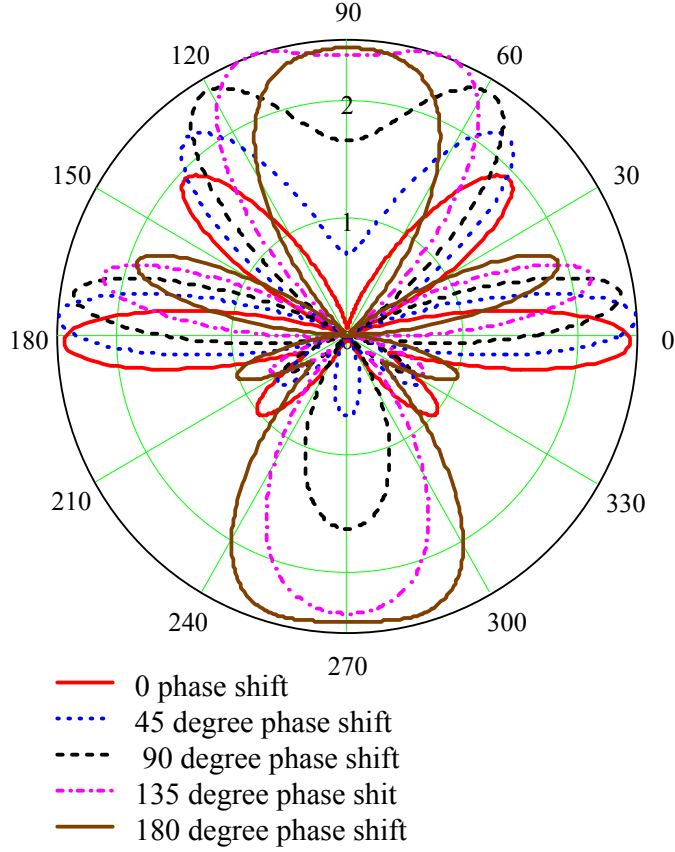
direction of the desired signal F_{array_b}, the three interferers ($F_{array_{i1}}, F_{array_{i2}} F_{array_{i3}}$) and ISR can be defined as:

$$F_{array_b} = A_1 + A_2 e^{i\psi_1} e^{-i2\pi\frac{d}{\lambda}\sin\phi_b} + A_3 e^{i\psi_2} e^{-i2\pi\frac{2d}{\lambda}\sin\phi_b} + A_4 e^{i\psi_3} e^{-i2\pi\frac{3d}{\lambda}\sin\phi_b}. \quad (3.5)$$

$$F_{array_{i1}} = A_1 + A_2 e^{i\psi_1} e^{-i2\pi\frac{d}{\lambda}\sin\phi_{i1}} + A_3 e^{i\psi_2} e^{-i2\pi\frac{2d}{\lambda}\sin\phi_{i1}} + A_4 e^{i\psi_3} e^{-i2\pi\frac{3d}{\lambda}\sin\phi_{i1}}. \quad (3.6)$$

$$F_{array_{i2}} = A_1 + A_2 e^{i\psi_1} e^{-i2\pi\frac{d}{\lambda}\sin\phi_{i2}} + A_3 e^{i\psi_2} e^{-i2\pi\frac{2d}{\lambda}\sin\phi_{i2}} + A_4 e^{i\psi_3} e^{-i2\pi\frac{3d}{\lambda}\sin\phi_{i2}}. \quad (3.7)$$

$$F_{array_{i3}} = A_1 + A_2 e^{i\psi_1} e^{-i2\pi\frac{d}{\lambda}\sin\phi_{i3}} + A_3 e^{i\psi_2} e^{-i2\pi\frac{2d}{\lambda}\sin\phi_{i3}} + A_4 e^{i\psi_3} e^{-i2\pi\frac{3d}{\lambda}\sin\phi_{i3}}. \quad (3.8)$$

$$A_4 = \sqrt{A_1^2 + A_2^2 + A_3^2}. \quad (3.9)$$

$$ISR = \frac{\sqrt{\left|F_{array_{i1}}\right|^2 + \left|F_{array_{i2}}\right|^2 + \left|F_{array_{i3}}\right|^2}}{\left|F_{array_b}\right|.} \quad (3.10)$$

In order to optimize the complex weights that include both amplitude and phase values and to minimize the interference, we performed constraint minimization of the ISR by using minimization functions available from software tools such as MATLAB or MATHCAD. These minimization functions allow one to search for optimized solutions for a non-linear function with some guessing of the initial values. To ensure that the weights amplitude conform to our normalization of gain power, we place a constraint of $0 < A_1, A_2, A_3 < 1$.

In the case of the 4-element array, there would be 6 unknown variables $(A_1, A_2, A_3, \psi_1, \psi_2, \psi_3)$ to be optimized, which effectively performs the null steering for the interferers. The most optimum strategy is to steer the null toward the interferer first rather than trying to maximize the gain of the desired signal beam.

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With the optimum weight values obtained after minimizing the ISR, these weights are back-substituted into Equations (3.5) and (3.6) to compute the optimum ISR (ISR_{opt}) and to obtain the antenna factor values for all directions.

B.   LINEAR ARRAY CONSTRAINTS

1.   Angular Spread and Null Depth
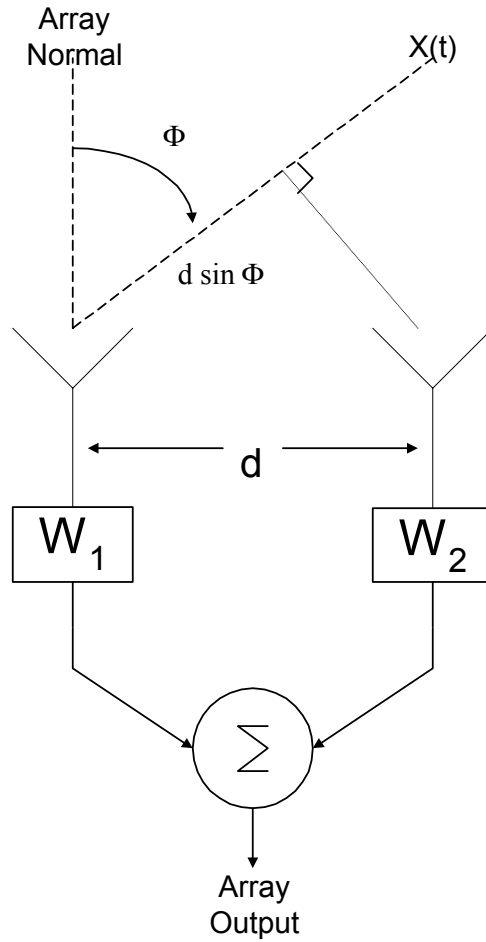
Figure 3.3   A 2-Element Array

To illustrate the angular spread problem of a linear array, we make use of a 2-element array as shown in Figure 3.3 with W_1 and $W_2 = 1$ for simplicity and let the left element output be $x_1(t) = x(t)$ as a reference, the output of the array

$$y(t) = x_1(t) + x_2(t) = \sum_{i=1}^{2} x(t) e^{j(i-1)\frac{2\pi d}{\lambda} sin\phi}.$$
(3.11)

The directional antenna pattern $G(\phi)$ can be defined as

$$G(\phi) = 10\,log\left|\frac{A(\phi)}{2}\right|^2 \quad [dB]$$
(3.12)

where

$$A(\phi) = \sum_{i=1}^{2} e^{\frac{j(i-1)2\pi d\,sin(\phi)}{\lambda}}.$$
(3.13)

If we take antenna separation of $d = \lambda/2$, $d = \lambda$ and $d = 2\lambda$, we can plot the directional pattern $G(\phi)$ versus ϕ as Figures 3.4 through 3.6.
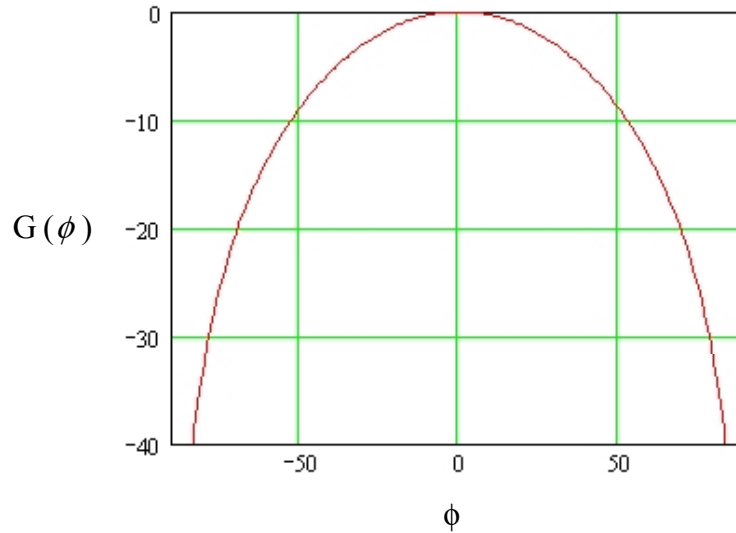
Figure 3.4   Directional Pattern for $d/\lambda=1/2$
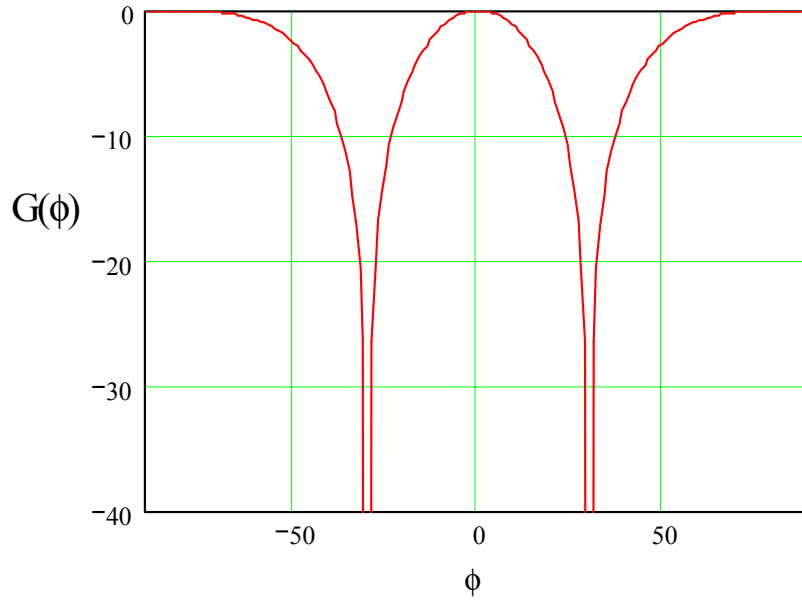
Figure 3.5　　　Directional Pattern for $d=\lambda$
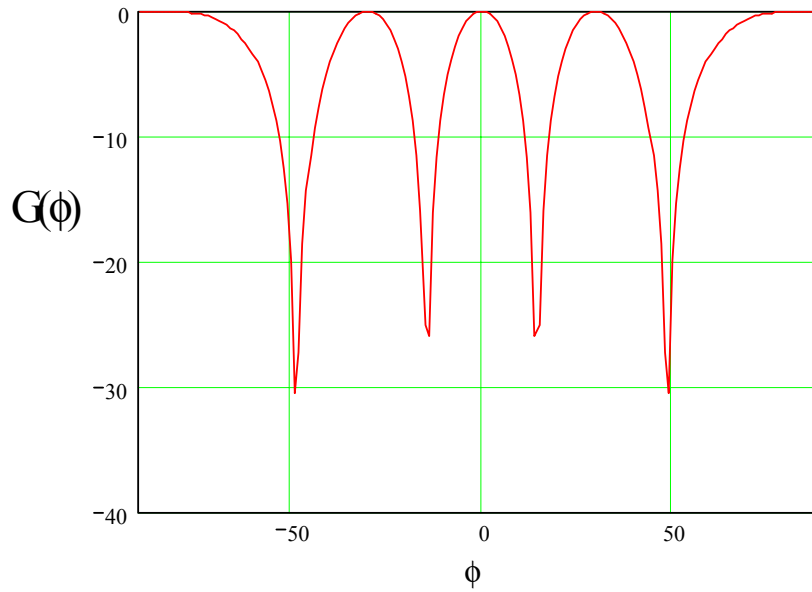
Figure 3.6　　　Directional Pattern for $d=2\lambda$

If the angular spread between the desired signal and the interferer is small, the antenna array may not be able to discriminate the interferer signal with deep nulls unless the antenna separation is increased.

For our system under analysis (as in Figure 3.1) with a 3-element linear array and antenna separation of $d= \lambda/2$, if we have a desired signal DoA at 0 degree azimuth and 2 interfering signals with a DoA at 125 and 360 degrees in azimuth, we can optimize an antenna factor plot as shown in Figure 3.7. We can achieve an ISR of 7.12 dB. When we increase the antenna separation for the system to $d= \lambda$, we can improve the ISR from 7.12 dB to −127.84 dB. In general, the antenna array can provide better interference cancellation if the antenna separation is increased, especially when the angular spread of the different sources are small. For comparison, Figure 3.7 and Figure 3.8 show that when the antenna separation d increases from $\lambda/2$ to λ, the adaptive array system can form a better focus beam and a deeper null.

Optimium Pattern for 3 Antenna Array with ISR = -7.1214 dB

Figure 3.7   3-Element Linear Array Antenna Factor with ISR = −7.21 dB and $d=\lambda/2$

Optimium Pattern for 3 Antenna Array with ISR = -127.8416 dB
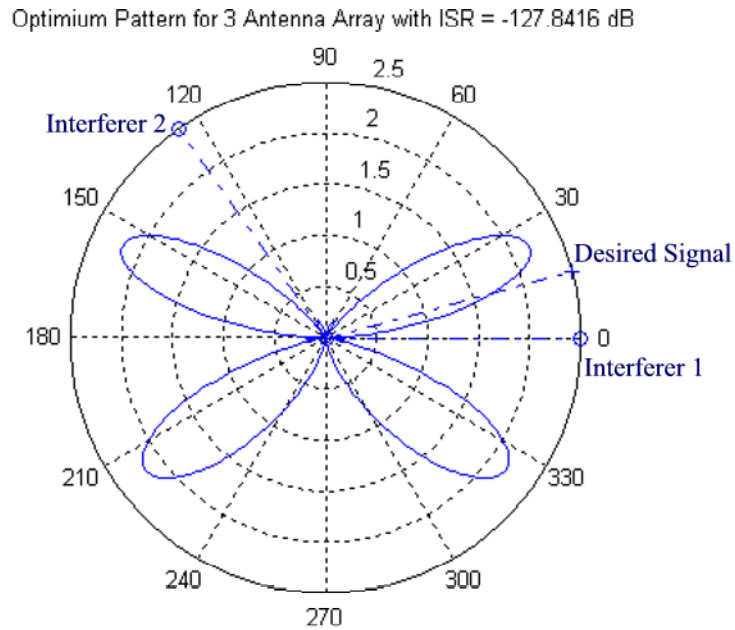
Figure 3.8   3-Element Linear Array Antenna Factor with ISR = −127.84 dB and $d = \lambda$

However, in our scenario as a mobile user, increasing the antenna separation is impossible in practice, because of the very limited real estate for the antenna site. For a mobile terminal such as a laptop PC, we can fit up to a 4-element linear array in about 30 cm, the width of a typical laptop, with a antenna separation of $d=\lambda/2$ when we operate in the frequency spectrum of 2 GHz. Doing this is impossible if we increase the antenna separation to $d= \lambda$, which requires a width of more than 30 cm in practice.

2.   Symmetry

Optimium Pattern for 3 Antenna Array with ISR = 0dB
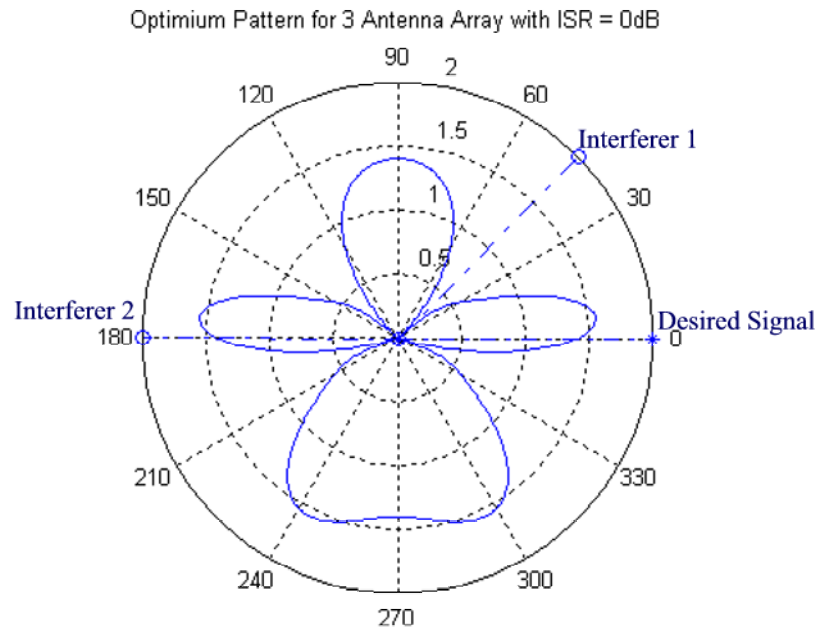
Figure 3.9   Symmetry Antenna Array Pattern

Figure 3.9 shows that the antenna pattern is always symmetrical on two sides from about 90 to 270 degrees axis. If the DoA of the desired signal and the interferer fall on the opposite side, both antenna factor and gain will be the same. In a worst-case situation in which the interferers are located in this symmetrical location and if the interferers are equal distance or equal signal power to the mobile as the SBS signal, the ISR will be close to zero which is not optimum. This situation occurs though it may be rare. It can be overcome if we allow the mobile to change the array orientation by some small value, which may improve the system's performance significantly.

3. Orientation Limited

Figures 3.10 and 3.11 illustrated that the linear array performance is orientation limited. Although the relative angular spread between the desired base-station and other interfering sources are the same, the performance of the ISR can be significantly different in both cases. This problem may be solved if the antenna array is rotated on the mobile for optimum performance.
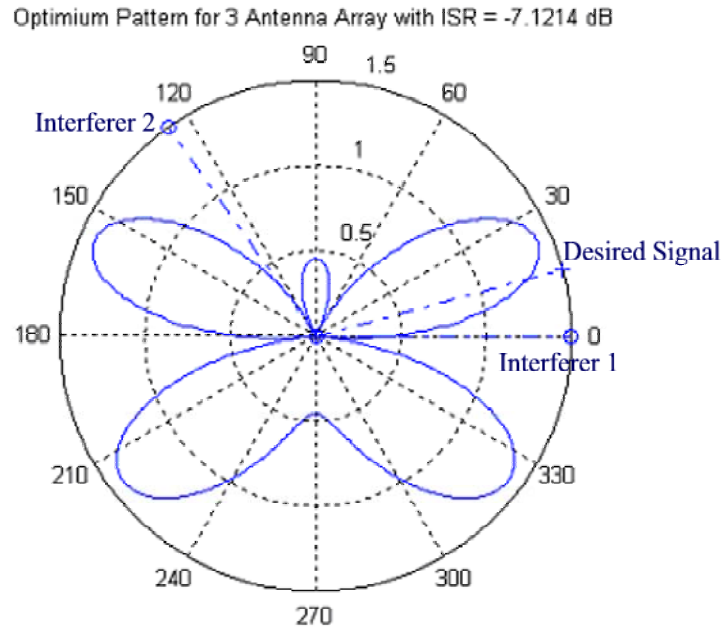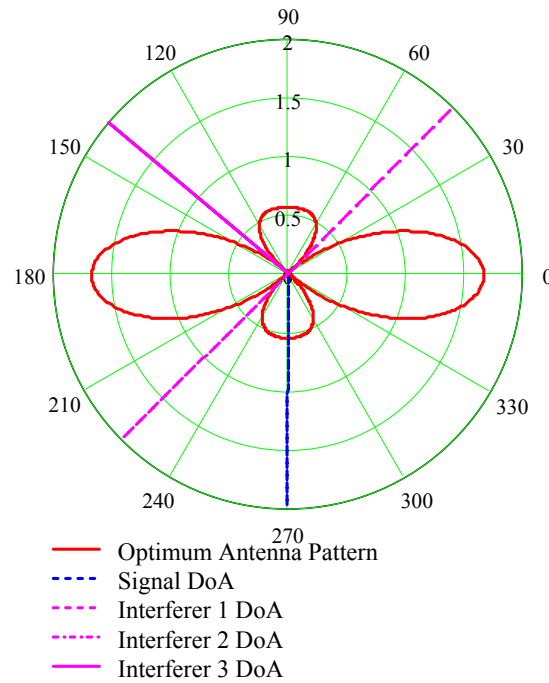

Figure 3.10   4-Element Linear Array Antenna Factor with ISR = −11.1 dB, $d=\lambda/2$
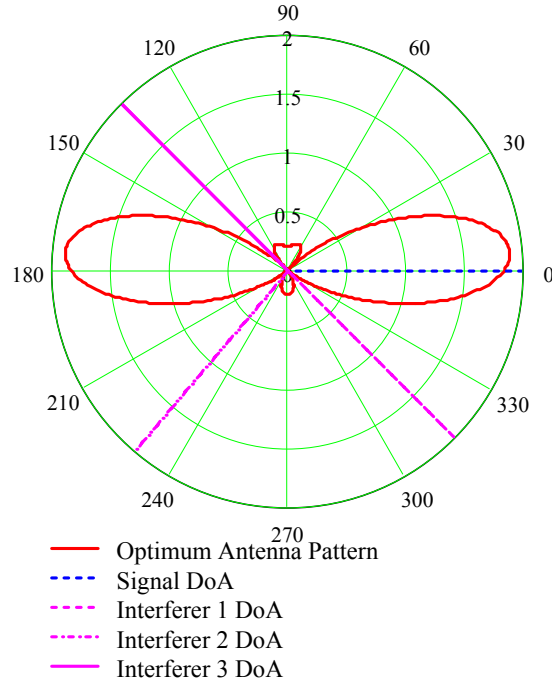
Figure 3.11   4-Element Linear Array Antenna Factor with ISR = −47.8 dB, $d=\lambda/2$

With the optimum complex weights determined for the adaptive antenna system, we noted that the depth of the null steer for suppressing interference depends on the geometry scenarios between the angular spread of the desired signal and interferers' DoA, the antenna-array arrangement and separation, and the geometric orientation between the array and all the other sources. All these factors contribute to the complexity of the operating environment to ensure a minimum system performance

We have discussed characteristics and constraints of an equally spaced adaptive array in this chapter. The orientation dependent linear array increases the complexity to ensure a minimum performance level within the cell. In the next chapter, we will discuss the forward channel model of the DS-CDMA system. This channel model will be used with the linear antenna array discussed for our performance analysis in Chapter V.

IV   FORWARD CHANNEL PROPAGATION MODEL FOR CDMA SYSTEM

The forward channel propagation model of a DS-CDMA mobile communication system in a slow, flat Rayleigh fading and log-normal shadowing environment is presented in this chapter. The forward channel is being studied because most data services are asymmetric, with the downstream requiring a higher data rate.

A.   MEDIUM PATH LOSS

In practice the mobile user can be located anywhere within the cell, with two degrees of freedom because its position can be at R distance from its base-station and can be at a particular angle to the base-station. Unlike an omni-directional antenna, the linear antenna array has an orientation, which must be considered. This directional effect of the linear antenna array increases the definition of the mobile position within the cell to a third-order problem since the mobile can be randomly orientated in any direction.

In order to account for co-channel interference, both the distances from the mobile to all 6 first-tier co-channel base-stations and their relative antenna array to base-station angle must be estimated.

We defined the distance from the base-station in the center cell to the mobile user as R, while the distance from the mobile user to the 1st tier co-channel base-station as D_i with the cell radius as D. The angle of the mobile from the base-station is A.

With the 6 first-tier hexagonal cells geometry fixed as their center base-station, we could determine all 7 angles and distances from the mobile to all the 7 base-stations when we define any position (R, A) in the center cell as a phasor representation of MS = R e^{jA} where ($0 < R < 1$) and ($0 < A < 2\pi$).

The distance D_i and the direction of arrival of the co-channel i-th base-station (BS) θ_i can be determined by using vector algebra.

With a normalized cell radius of $D = 1$, the distance between the center of each adjacent base-station is $\sqrt{3}$ and the angle from the center origin to each adjacent base-station, θ_{BSi}, is at $(0, \pi/3, 2\pi/3, \pi, 4\pi/3, 5\pi/3, 2\pi)$ radians, we could determine all the look angles and the distances from the mobile-station to all adjacent base-stations.

$$D_i = \text{Re}|\sqrt{3}\, e^{j\theta_{BSi}} - R\, e^{jA}\,| \qquad (4.1)$$

$$\theta_{BSi} = (0, \pi/3, 2\pi/3, \pi, 4\pi/3, 5\pi/3, 2\pi) \qquad (4.2)$$

$$\theta_i = \angle(\sqrt{3}\, e^{j\theta_{BSi}} - R\, e^{jA}\,) \qquad (4.3)$$

The azimuth and distance toward the desired center base-station is

$$\theta_{BS} = \pi + A \qquad (4.4)$$

$$D_{BS} = R\,. \qquad (4.5)$$

These distances and angles are used to calculate the path loss for the desired signal and co-channel interference using the Hata model, which is equivalent to an average path loss $L_n(D)$ [7] with a path loss exponent of $n=4$.

$$L_n(D) \propto \left(\frac{D}{d_o}\right)^n \qquad \text{where } d_o \text{ is the reference distance.} \qquad (4.6)$$

1. **Hata Model**

The Hata model is one of the simplest and most accurate empirical models for representing path loss of cellular systems as presented in [7]. It is based on Okumura model's graphical path loss data [1] using a standard formula for an urban operating area and other areas with modified equations. The original Hata model matches the Okumura

model closely for distances greater than 1 km, and the extended model [2] further extends to cover higher frequency ranges with distances of about 1 km. In this thesis, we use the extended model as it better represents the operating environment of a 3G cellular system.

The extended Hata model, which predict the median path loss $\mathcal{L}_\mathbf{H}$ in dB as defined in [7] by

$$\mathcal{L}_\mathbf{H} = 46.3 + 33.9 \log f_c - 13.92 \log h_{base} - a(h_{mobile}) \tag{4.7}$$
$$+ (44.9 - 6.55 \log h_{base}) \log d + C_M$$

where

$$a(h_{mobile}) = (1.1 \log f_c - 0.7) \, h_{mobile} - (1.56 \log f_c) \quad \text{(dB)} \tag{4.8}$$

and

$$C_M = \begin{cases} 0 \text{ dB, for medium sized city and suburban areas} \\ 3 \text{ dB, for metropolitan areas.} \end{cases}$$

Note that

f_c : carrier frequency in MHz,

h_{base} : base-station antenna height in meters (m),

h_{mobile} : mobile-station antenna height in meters (m), and

d : separation distance is measured in kilometers (km).

The extended Hata model is restricted to the following range of parameters:

f_c :   1500 MHz to 2000 MHz

h_{base} :   30 m to 200 m

h_{mobile} :   1 m to 10 m

d :   1 km to 20 km

We chose the mobile and base-station heights of 1 m and 30 m respectively with an operating carrier frequency of 2000 MHz for all our research.

2.   Log-normal Shadowing

Log-normal shadowing accounts for variation in the average large-scale propagation fading for a given distance. The actual path loss for a mobile user in different locations but with the same distance from the base-station varies due to the medium. This happens because the terrain variations in a particular path can be significantly different from the predicted average path loss. A Gaussian random variable $\mathcal{X}$ with zero-mean and σ_{dB} standard deviation can be used to represent the shadowing of the average path loss value. The path loss with shadowing accounted for is modeled by

$$\mathcal{L}_X(D) = \mathcal{L}_H(d) + \mathcal{X} \quad (dB) \tag{4.9}$$

where

$\mathcal{L}_H(D)$ is the average path loss at distance D km.

The above equation can be converted to a log-normal random variable L_X as defined in [4]

$$L_X = L_H X. \tag{4.10}$$

The above log-normal random variable L_X in (4.10), which accounts for the effect of log-normal shadowing with the Hata model, can then be applied to the signal in the forward channel of the DS-CDMA cellular system in a Rayleigh slow-flat fading environment.

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B. FORWARD CHANNEL MODEL

In [4], the above both large-scale and small-scale propagation effects are combined into a single model. This combined Rayleigh-log-normal channel fading model allows us to characterize the mobile radio channel accurately in a single unified model, in which we can more completely analyze the mobile radio channel.

The Rayleigh-log-normal channel model is then applied to a typical DS-CDMA cellular system consisting of traffic from a cell's base-station to the mobile users in the cell, which characterize the received signal of a mobile user. This received signal includes both traffic intended for the mobile user from the Signal Base-Station (SBS), traffic from other users in the cell (intra-cell interference), traffic for users in adjacent cells (inter-cell interference) and additive white noise. The Signal-to-Noise plus Interference Ratio (SNIR) and Bit Error Rate (BER) for the DS-CDMA forward channel in the Rayleigh-lognormal fading channel were derived in [4].

Using the Forward Error Correction (FEC) the upper bound bit error probability P_e is defined in [4]:

$$P_e \le \frac{1}{k} \sum_{d=d_{free}}^{\infty} \beta_d P_2(d).$$

(4.11)

$$P_2(d) = \int_{-\infty}^{\infty} Q(\sqrt{\frac{z_d}{\alpha}}) P_{z_d}(z_d) dz_d.$$

(4.12)

$$\alpha = \frac{e^{(\frac{\lambda^2 \sigma_{dB}^2}{2})}}{3N} \sum_{i=1}^{6} \sum_{j=0}^{K_i-1} \frac{L_H(D)}{L_H(D_i)} + \frac{N_o}{2E_c}.$$
 (from [4] equation (4.60))   (4.13)

$$E_c = \frac{kE_b}{n} \text{ is the coded bit energy.}$$

(4.14)

$$\lambda = \frac{\ln 10}{10}. \tag{4.15}$$

where $P_2(d)$ is the first-event error probability of the random variable Z_d, which is the sum of d multiplicative chi-square (with 2 degrees of freedom) log-normal random variables. The details of the derivation and modeling of Z_d are elaborated in [4]. β_d is the total number of information bit errors that is associated with selecting a path of distance d from the all-zero path, which can be calculated for a particular convolutional code. σ_{dB} is the log-normal shadowing random variable standard deviation in decibels (dB).

However, when we incorporate the use of smart antenna in our case, the above model must be modified to take into consideration the antenna gain factors for all 6 co-channel interference base-stations (IBS). Hence our modified α becomes

$$\alpha' = \frac{e^{\left(\frac{\lambda^2 \sigma_{dB}^2}{2}\right)}}{3N} \sum_{i=1}^{6} \sum_{j=0}^{K_i-1} \frac{L_H(D)}{L_H(D_i)} \frac{G_i}{g} + \frac{N_o}{2E_c}. \tag{4.16}$$

where G_i and g is the antenna gain factor for IBS$_i$ and Signal Base-Station (SBS), respectively.

We required optimization of the linear antenna array over a 360-degree orientation for any mobile user positions within the center cell of a 7-cell cluster. Since the path loss from the various mobile positions to the different IBSs, the SBS and the respective directions are different and we must derive an antenna-array optimization constraint, which accounts for all the above possible variations. Simple optimization using antenna factor interferer-signal-ratio (ISR) may not be appropriate because it did not account for the different path loss values for the different interferers.

For simplicity, we assume all first-tier cells around the SBS's center cell have the same number of active users in each cell. We define the Path Loss Ratio (*PLR*) as the optimization factor for determining if the particular orientation of a particular position is the best or the worst in performance.

$$PLR = \sum_{i=1}^{6} \frac{L_H(D)}{L_H(D_i)} \frac{G_i}{g} . \tag{4.17}$$

Note that α' is proportional to *PLR,* where the former is the denominator in the Q function of the first-event probability $P_2(d)$ in Equation (4.12). Thus, if *PLR* is smaller, $P_2(d)$ will be smaller and since the probability of error P_e is also proportional to $P_2(d)$, as defined in Equation (4.11), if $P_2(d)$ is smaller, P_e will show better performance.

Now we are ready to establish performance boundaries based on the *PLR* values after the antenna array optimization. Due to the complexity of the above channel model, we could not reasonably develop any analytical solutions. Instead a Monte Carlo simulation was used to obtain the solutions for our performance analysis in Chapter V.

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V   PERFORMANCE ANALYSIS OF ADAPTIVE ANTENNA SYSTEM

In this chapter, we assess the performance on the forward channel with equally spaced linear smart antenna arrays at the mobile user within the cell. Analyzing the forward channel with an adaptive array is complex, as the channel is wireless, the position of the user is mobile, and the orientation of the array is random. As discussed in Chapter IV, we use the DS-CDMA forward channel model developed in [4], for a received signal at the mobile user in a Rayleigh-lognormal channel. The BER performance with different linear arrays was statistically simulated due to the complexity of our channel model as no analytical solutions can be reasonably developed. Since thousands of possible locations can exist within the cell, and since each position can have random orientations that affect the linear antenna array ISR, evaluating the overall system BER performance can be extremely computational expensive. Obtaining a good representation of the result is also difficult because the BER performance at each location may deviate significantly with a different orientation. Also the adaptive linear array may encounter constraints, so it cannot effectively cancel the interferers, such as in the situation mentioned in Chapter III where an interferer and desired signal are located in the mirror symmetry position at an equal distance. We have adopted a 4-boundary approach to better represent the adaptive-array system performance for our evaluation and provide comparison with a system without using the smart antenna.

Initially, we analyze the performance boundary for a 2-, 3- and 4-element linear array by positioning the Mobile Station (MS) randomly within the cell, with the MS being rotated 360 degrees at each location. We perform the adaptive array optimization for each random MS position at each orientation, with 1-degree resolution for the whole 360-degree orientation. For each of the optimized weights obtained for each 1-degree orientation, we use the optimized weights to compute the antenna gain for all the 7 antenna-array factors, to determine the path loss ratio as defined in Chapter IV. We repeat the process for 360 degrees. We then select the best and worst path-loss ratio that correspond to the best and worst system performance for that single location.

We also repeat the whole optimization process to capture the best and the worst performance by positioning the MS around the boundary of the cell within a 60-degree sector, assuming the furthest distance from the signal BS has a normalized radius of 1 km and the nearest distance of 0.1 km. We also confine the random position to fall within the 60-degree sector, as the hexagonal cell is symmetrical in all such 60-degree sectors and the performance analysis on one of the 60-degree sectors could apply to all the cells without losing any generality.

We then sort each lot of the path-loss ratios by determining the largest and smallest path-loss ratio values to obtain 4 path-loss ratio values. These 4 path-loss ratio values are used to perform the Monte Carlo simulation on Equation (4.11) to obtain BER performance boundaries for the DS-CDMA mobile communication system forward channels of the mobile user with adaptive linear array with different operating scenarios. The 4 boundaries are defined as:

1.   Best of Best BER boundary (BB)
2.   Worst of Best BER boundary (WB)
3.   Worst of Worst BER boundary (WW)
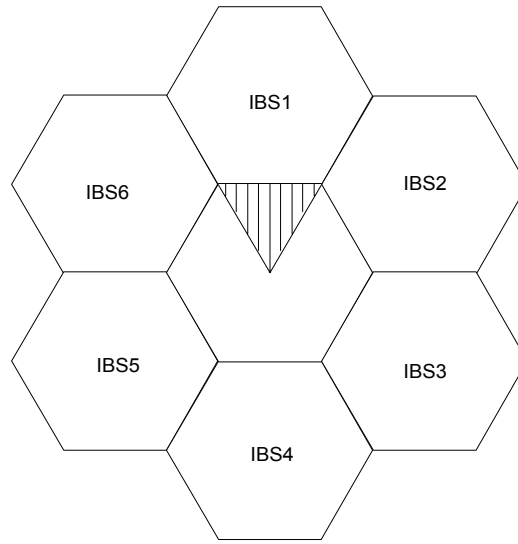4.   Best of Worst BER boundary (BW)

Figure 5.1   Area of Analysis within a Cell

Without losing generality, we can take the sector, as indicated in Figure 5.1, as the area for analysis since all other sectors are symmetry. The system performance analyzed for the selected sector is applicable to other sectors within the same cell. We can see that of the 4 boundaries illustrated in Figure 5.2, the WW boundary, being far above the chart of BER=10^{-1}, is not visible. The Best of the Best (BB) boundary, representing the very best performance, is the performance ceiling of the system as it cancels the dominant co-channel interference extremely well. The location of this point is at the nearest point within 10% of the normalized radius. For the 2-element array, the BB is at the azimuth along the line between the SBS and the IBS. This is not surprising since the nearest IBS 1 interference is being attenuated by the null, which the adaptive-array system steers. In the case of the 3- and 4-element array, the BB point is at 120 degrees and 90 degrees with 10% of the normalized radius. This indicates that all the nearest IBS co-channel interferences are effectively cancelled. We can also look at this performance bound as the achievable performance for a linear array is given 360 degrees of freedom.
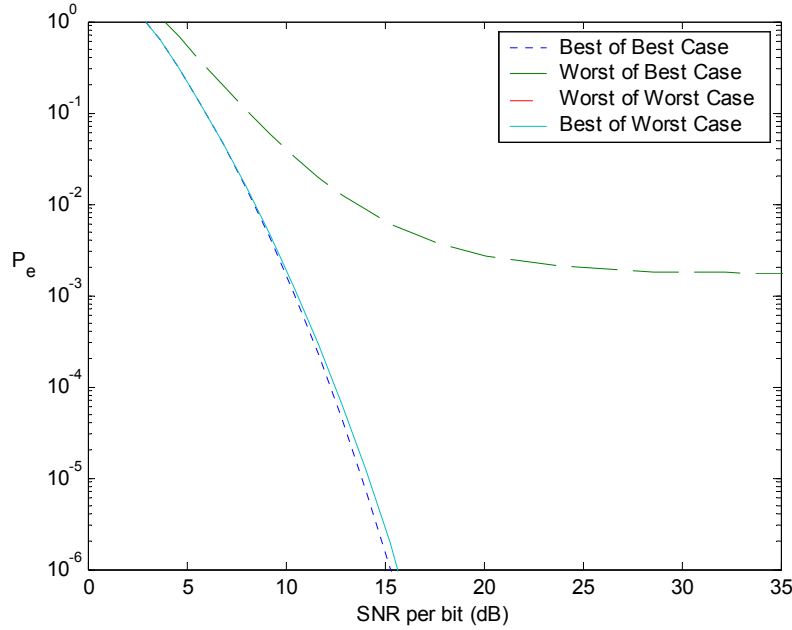
Figure 5.2   Forward Channel Performance Boundaries for Our DS-CDMA System with a 4-Element Linear Adaptive Array System (σ_{dB}=7, *Rcc*=1/2, *v*=8)

The Worst of the Worst (WW) case is a very pessimistic scenario in which the interferer is not being suppressed or perhaps is being amplified by the adaptive array. The constraints of the linear array, such as the symmetry of IBS and SBS locations or a poor initial guess for minimizing the ISR ratio etc. might cause this. The performance of this case is always above the usable limit of the BER of 10^{-2}. The location of this case is near the edge of the cell adjacent to the other co-channel IBS cell. For 2- and 4-element arrays, the WW point is near the cell corner, adjacent to the two other IBS cells whereas for the 3-element array, the WW point is located at the mid-point between the SBS and IBS lines. This boundary is not usable to represent the performance of the system reasonably. We shall review the WW case in a later section, which indicates that the WW case indeed is not as pessimistic as it appears, especially if we have some degree of freedom to adjust or to rotate the antenna array. This bound can also be viewed as the worst performance boundary if the linear array of the mobile unit is fixed in its orientation. This may not be the case in a field system.

The Best of the Worst (BW) boundary is generally very much like the BB case that is usually close to the ceiling performance boundary. The best result of any scenario is located closest to the 10% radius of the SBS where the low path loss for the desired signal dominates the interference signals generated by other IBS. The BER performance for all scenarios for the BW case thus falls very close to the BB boundary, as in both cases, the co-channel interferences are very effectively cancelled.
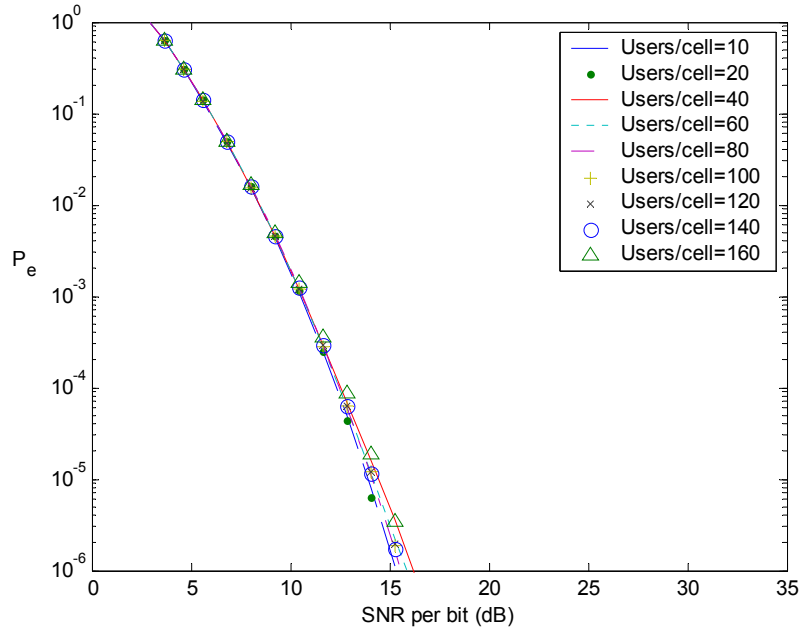

Figure 5.3   BW Boundaries for a 4-Element Adaptive Array System(σ_{dB}=7, Rcc= ½, v=8)

The most representative boundary is the Worst of Best (WB) case as it indicates system performance that is neither too pessimistic nor too optimistic. As in the usual design of a mobile communication system in which we are interested in the minimum assured performance, the WB boundary provides that minimum boundary. This WB boundary indicates the worst case (the lowest limit) of the best performance achievable by our system with a linear array with 360 degrees of freedom. The location of the WB cases is at hexagon cell corner for a 2- and 3-element array and at the mid-point between the IBS and the SBS line. The WB BER boundary is used in most of our analysis.

Figures 5.4, 5.5 and 5.6 illustrate the performance of the WB probability boundaries for all three configurations against the average SNR per bit for a different number of active mobile users. We can see that for a given level of BER and a given number of active users, the corresponding average SNR per bit can be determined for each configuration.

Figure 5.4   WB Performance Boundaries for Our DS-CDMA System with a 2-Element Linear Adaptive Array System (σ_{dB}=7, Rcc= ½, v=8)

Figure 5.5   WB Performance Boundaries for Our DS-CDMA System with a 3-Element Linear Adaptive Array System (σ_{dB}=7, *Rcc*= ½, *v*=8)
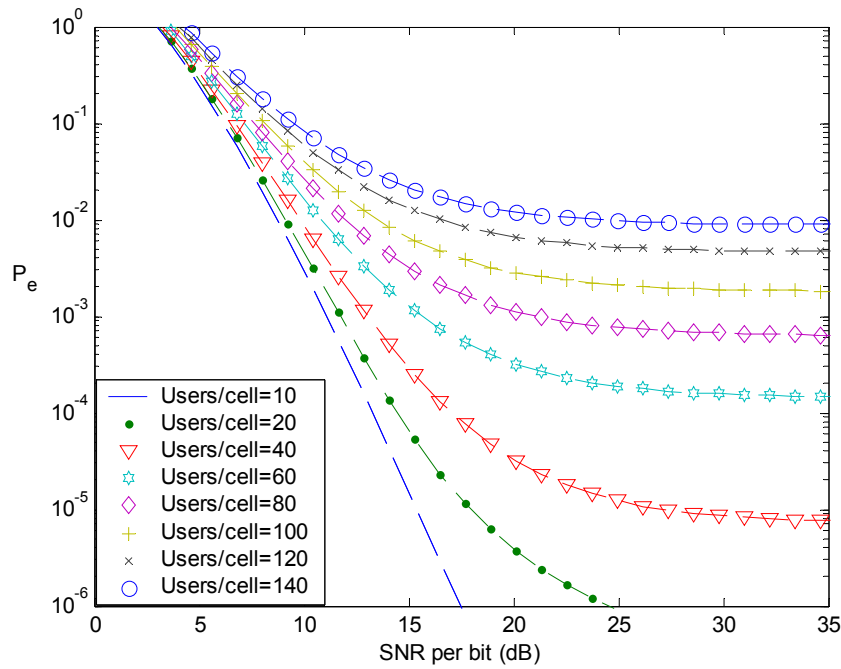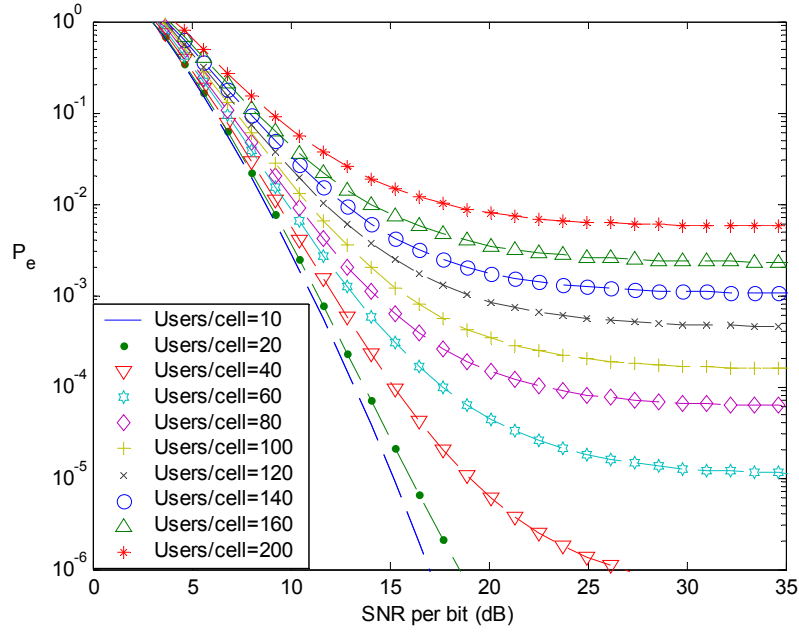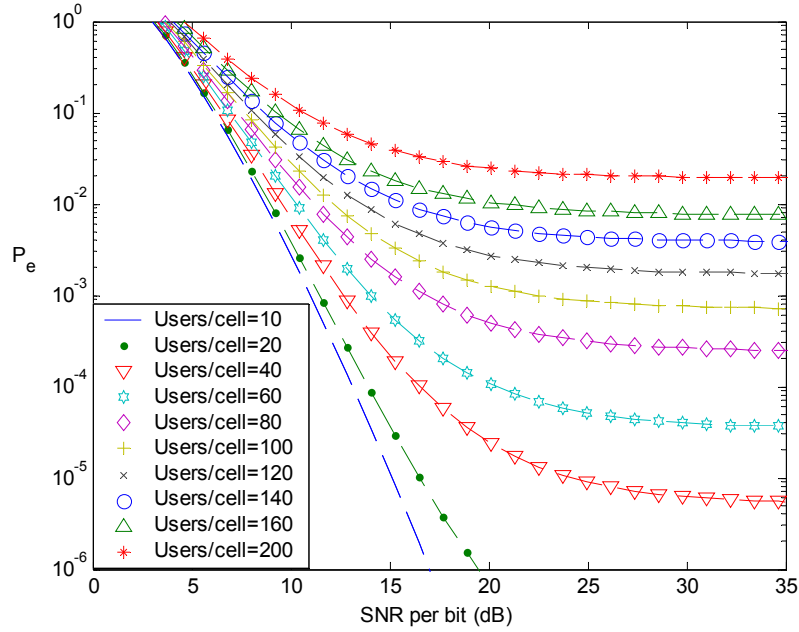

Figure 5.6   WB Performance Boundaries for Our DS-CDMA System with a 4-Element Linear Adaptive Array System (σ_{dB}=7, *Rcc*= ½, *v*=8)

It is interesting to note that the WB path-loss ratio obtained from the optimization of a 3-element array is slightly smaller than the 4-element array and will provide better BER performance than the 4-element array configuration. This may be possible due to the non-linear ISR optimization, which steers the different nulls toward different interferers. The optimized null depths, which depend on the initial guess values, the number of interferers, and the relative MS/IBS/SBS orientation are very much algorithm dependent. This illustrates the complexity of analyzing a system that depends on multiple factors, each affecting its overall performance. Nevertheless, the antenna array with more elements can suppress more interferers and generally offers better overall system performance everywhere within the cells. However, the worst-case situation of a 4-element array system here may not be better than a 3-element system.

We compare the performance of the DS-CDMA system with FEC in terms of the number of users per cell that can be supported at a SNR per bit of 15 dB with a shadowing of σ_{dB} =7 dB for a system with and without the linear array. When the number of mobile user increases, the inter-cell interference increases and deteriorates the probability of bit error. We could then determine the number of active users allowed in order to ensure a desired level of probability of error for the given operating environment and configuration.

We can see that the system capacity with adaptive arrays can increase the number of active mobile users for BER of 10^{-3} or less in a system without an array of 13 to 80 and 125 for a system with 2- and 3-element arrays in Figure 5.7. The capacity gained from the use of a 2-element adaptive array is an impressive capacity gain of about 600% over a system without an adaptive array. If a 3-element array is used, the gain in capacity at the same BER performance is even higher (900%). This demonstrates the strength of the adaptive-array application in a mobile communication system and its potential for improving the system's capacity.
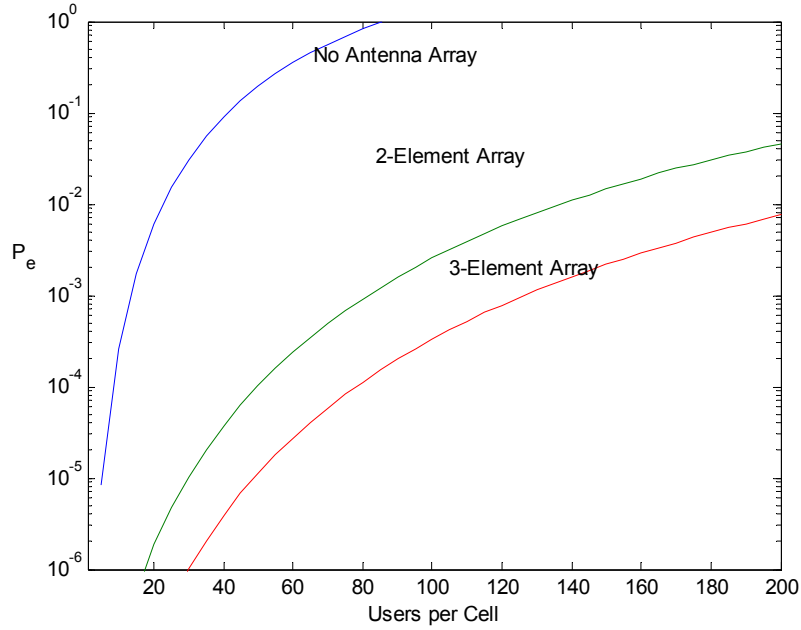
Figure 5.7   Probability of Bit Error for DS-CDMA System with a SNR per Bit of 15 dB

(σ_{dB}=7, *Rcc*= ½, *v*=8).

Sectoring, which can limit the amount of inter-cell interference, was also performed on the adaptive-array system with 3 and 6 sectors. Figures 5.8, 5.9 and 5.10 illustrate the WB probability of bit error versus the number of users for a system with a 2- and 3-element linear adaptive array in the DS-CDMA forward channel, as compared to the system with a single omnidirectional antenna as present in [4] at an average SNR per bit of 15 dB with a fading parameter σ_{dB} =7 dB.

We can observe the dramatic improvement in the system's capacity with the use of an adaptive array for all 3 configurations with sectoring cells, when we assume that the users are uniformly distributed. We can see that the system with a 2-element array can accommodate 80 active users with no sectoring at BER of 10^{-3} and can increase the system capacity rapidly when sectoring is applied. Interestingly, we can observe that the performance of the 2-element array without sectoring is very close to the system without an adaptive array but with 60-degree sectoring.

Figure 5.8   Probability of Bit Error for a 2-Element Linear Adaptive Array DS-CDMA
System Using Sectoring with a SNR per Bit of 15 dB (σ_{dB}=7, Rcc= ½, v=8).
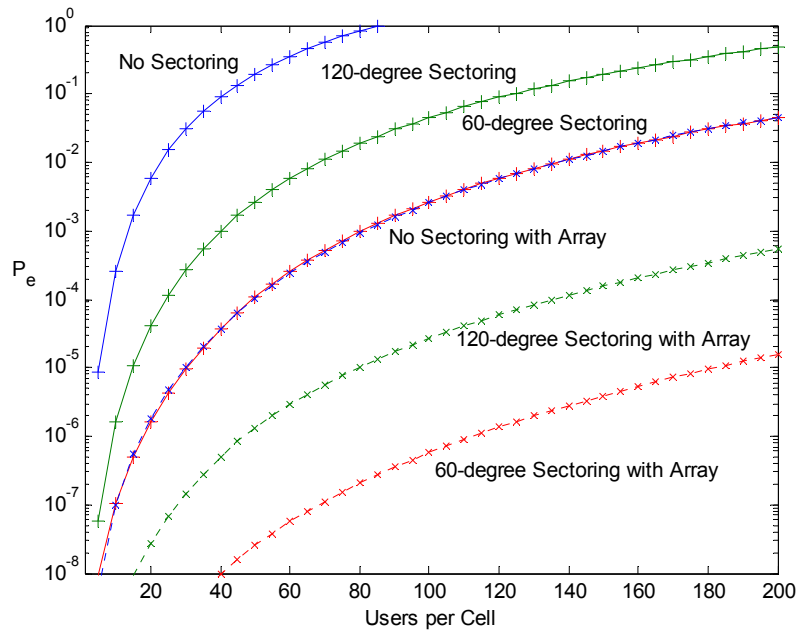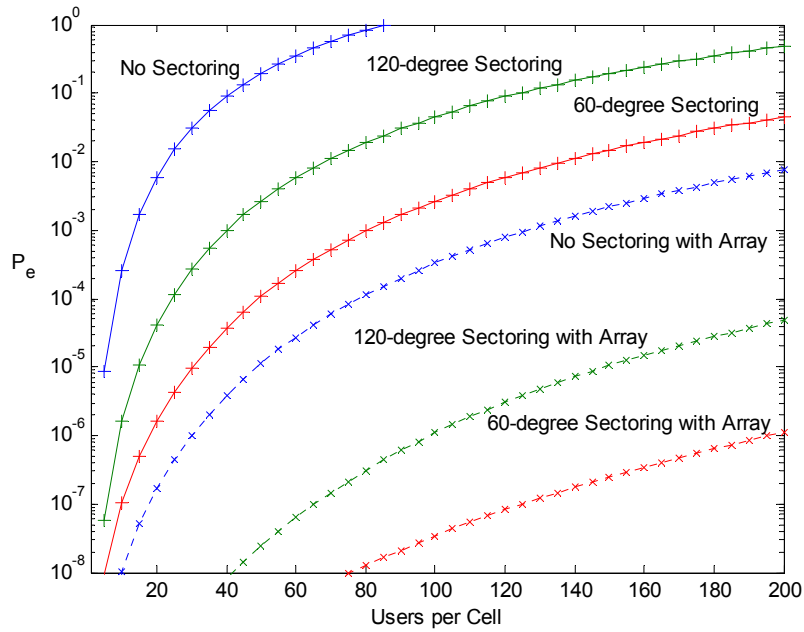

Figure 5.9   Probability of Bit Error for a 3-Element Linear Adaptive Array DS-CDMA
System Using Sectoring with a SNR per Bit of 15 dB (σ_{dB}=7, Rcc= ½, v=8).

When the adaptive array is applied, the DS-CDMA system can provide good performance because of interference suppression, which allows it to tolerate other constraining factors, such as fade depth. If the shadowing parameter σ_{dB} is increased to 9 dB, which corresponds to an environment with a deeper fading variation, we can see that the 2-element array system's capacity without sectoring will reduce from 80 ($\sigma_{dB} = 7$) to 30 active users at BER of 10^{-3} (see Figure 5.10). This is close to a system without an adaptive array, but with 120-degree sectoring at $\sigma_{dB} = 7$ dB. For the case of a 3-element array system, when the shadowing parameter σ_{dB} is increased from 7 dB to 9 dB, the maximum number of active users for the system at BER of 10^{-3} dropped from 120 to 48, as in Figure 5.11.

Figure 5.10   Probability of Bit Error for a 2-Element Linear Adaptive Array DS-CDMA System Using Sectoring for $\sigma_{dB} = 9$ dB with a SNR per Bit of 15 dB ($Rcc = 1/2$ and $v = 8$).
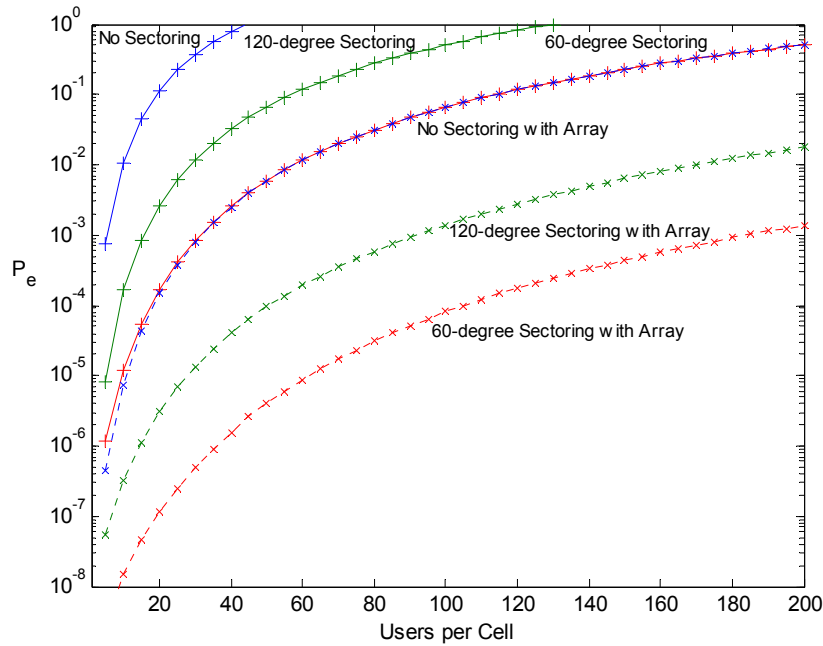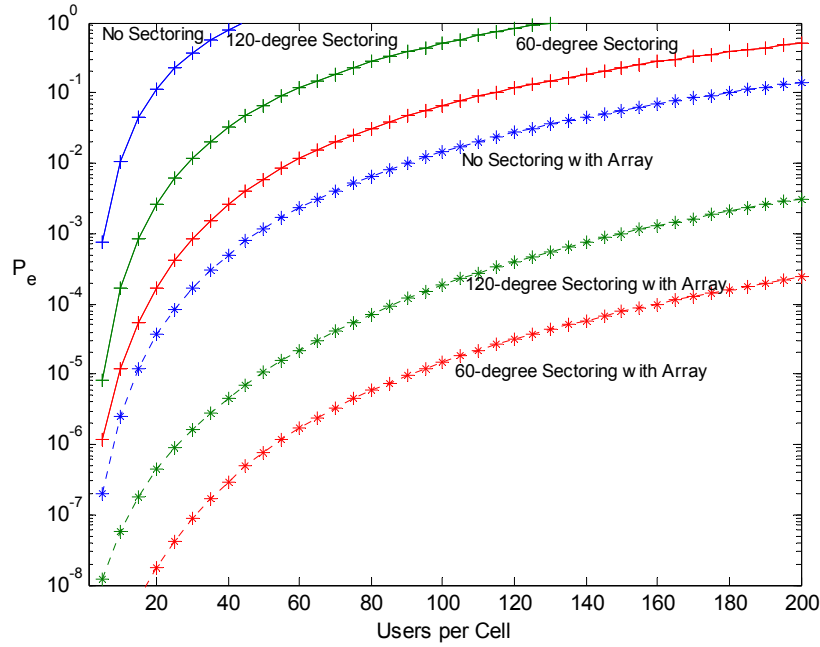
Figure 5.11   Probability of Bit Error for a 3-Element Linear Adaptive Array DS-CDMA System Using Sectoring for $\sigma_{dB} = 9$ dB with a SNR per Bit of 15 dB (*Rcc* = 1/2 and *v* = 8).

We also took a closer look at the WW boundary that corresponds to a scenario in which the mobile is fixed at a certain worst-performance orientation that is usually not realistic practically. If we allow the MS or antenna array some degree of rotational freedom, such as ± 5 degrees, in the 3-element array configurations, we should be able to improve the WW BER performance. We perform an antenna optimization analysis with ±5 degrees in 1-degree step size at the WW position. We collected all 11 path-loss ratios (PLR), as illustrated in Table 5.1. Using the worst-case scenario in [4] as a reference in which the system without a smart antenna array has a PLR of 2.239, 8 out of the 10 optimizations performed with the PLR are better than the reference.

Orientation Offset	Path Loss Ratio
+5	1.3518
+4	1.3588
+3	1.4300
+2	9.2091
+1	10.6014
WW case	19.8476
−1	1.0877
−2	1.1107
−3	1.3611
−4	1.3560
−5	1.3532

Table 5.1   3-Element Array Path-Loss Ratio Values for Different Orientation Offset in the WW Case
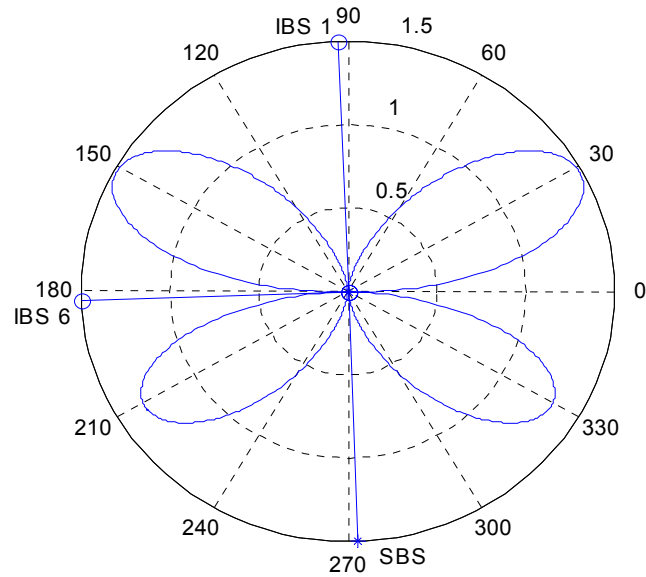
Figure 5.12   Antenna Factor of the WW Case for a 3-Element Array Antenna with a
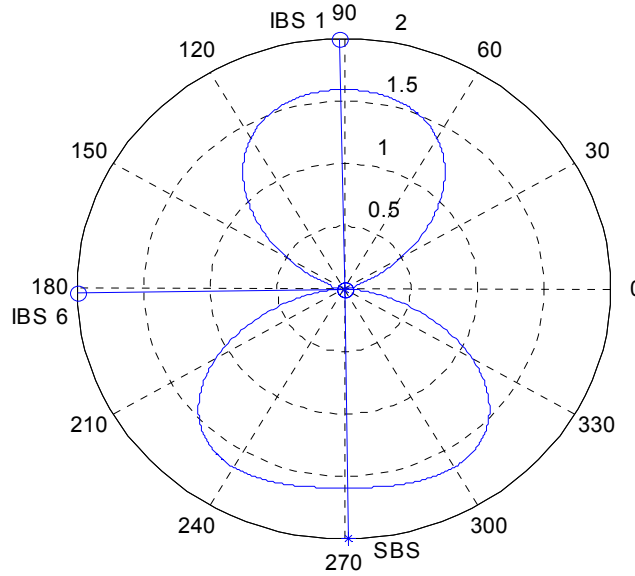
Path-Loss Ratio of 19.8476

Figure 5.13   Antenna Factor of the WW Case for a 4-Element Array Antenna at −1

Degree Offset with a Path-Loss Ratio of 1.0877

Figure 5.12 shows the antenna factor for the WW location (R =0.866, A=90 degree) at array orientation of 2 degrees for a 3-element linear array. Figure 5.13 shows the antenna factor when the array is rotated for −1 degree. We can observe that the array factor patterns are significantly different with just 1-degree difference in orientation. We repeat the analysis process at the WW case position for the 2-element and 3-element array. We observed similar characteristics where the WW-case Path-Loss Ratio is reduced significantly within a small ±5 degree orientation offset, which is reasonable in a practical implementation. Hence the Worst-Worst case BER performance can be improved significantly with such a practical allowance. Table 5.2 shows that we can obtain many path-loss ratios that are less than the worst-case situation for a DS-CDMA system without a linear array of 2.239. Hence with the ± 5 degrees of orientation offset, we can observe that the worst performance of a system with the linear array in practice will always be better than a system without the smart antenna.

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Orientation Offset	Path-Loss Ratio		
	2-Element Array	3-Element Array	4-Element Array
+5º	0.6147	1.3518	1.8762
+4º	0.5983	1.3588	2.0265
+3º	0.5826	1.4300	6.1393
+2º	0.8634	9.2091	7.8293
+1º	0.8634	10.6014	0.7950
WW case	661.2276	19.8476	185.6
−1º	6.3172	1.0877	12.8122
−2º	3.1465	1.1107	0.6293
−3º	2.0834	1.3611	5.4201
−4º	1.5512	1.3560	3.9677
−5º	1.2318	1.3532	3.0803

Table 5.2   Path-Loss Ratio Values of a 2-, 3- and 4-Element Array with a Different Orientation Offset at the WW Case

In Figures 5.14 to Figure 5.16, we observe similar characteristics for a 4-element array system with a few degrees of orientation offset in the WW case position. We can see drastic changes in antenna factor patterns that allow the system to reduce the PLR significantly from 185.6 when the array is rotated by +1 or −2 degrees to 0.795 and 0.6293 respectively.
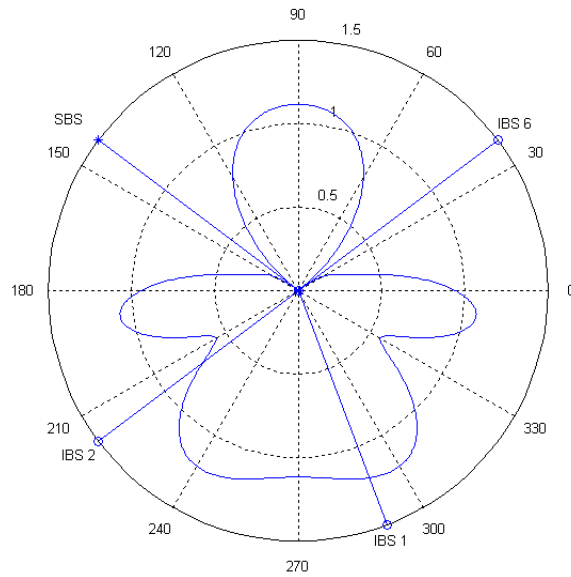
Figure 5.14   Antenna Factor of the WW Case for a 4-Element Array Antenna with a
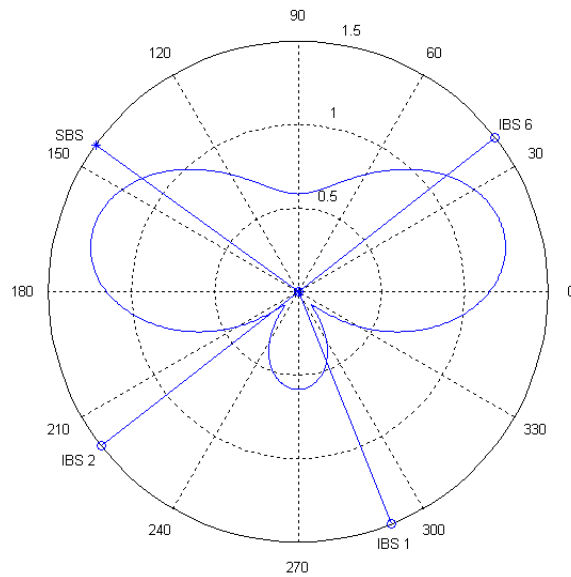Path-Loss Ratio of 185.6

Figure 5.15   Antenna Factor of the WW Case for a 4-Element Array Antenna at +1
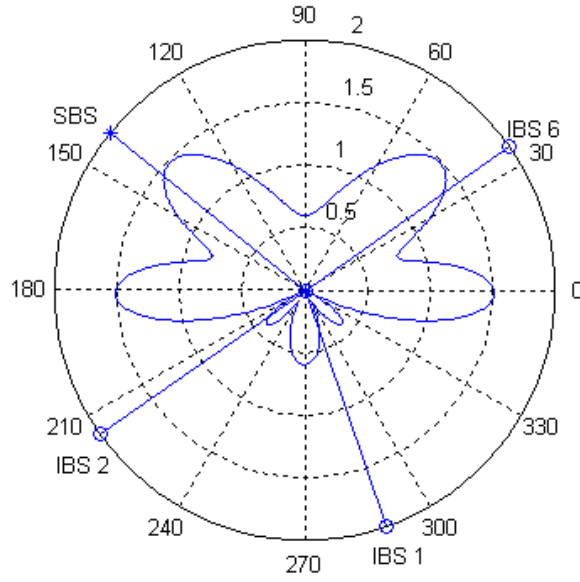Degree Offset with a Path-Loss Ratio of 0.7950

Figure 5.16 Antenna Factor of the WW Case for a 4-Element Array Antenna at −2 Degree Offset with a Path-Loss Ratio of 0.6293

In Figures 5.17 to 5.19, the DS-CDMA system's BER performance with a different number of elements array within ±5 degrees of the WW case orientation is illustrated. This is used to compare the worst-case performance of a system without an array as in [4]. The comparisons demonstrate the strength of the optimization algorithm, which allows the system to escape the WW case with good system performance with a small change in the orientation angle. We can see that the practical worst case of a 4-element array system without any sectoring has the same capacity as a system without an array but with 120-degree sectoring. However when 120-degree sectoring is used in the 4-element array system, the system capacity of 110 active users exceeds the maximum capacity of 80 active users of the system without an array but with 60-degree sectoring. Table 5.3 summarized the simulation results.

Active Users	Without Array	2-Element Array	3-Element Array	4-Element Array
No Sectoring	13	51	27	40
120 degree Sectoring	40	150	84	110
60 degree Sectoring	80	>200	170	>200

Table 5.3   Linear Array System Capacity Enhancement with ±5 Degree Freedom about the WW Case Location at BER 10^{-3} (σ_{dB} = 7 dB, Rcc = 1/2 and v = 8)

Figure 5.17   System Enhancement with +3 Degree of Orientation Offset at Worst-Worst Case for a 2-Element Array (σ_{dB}=7, Rcc= ½, v=8)
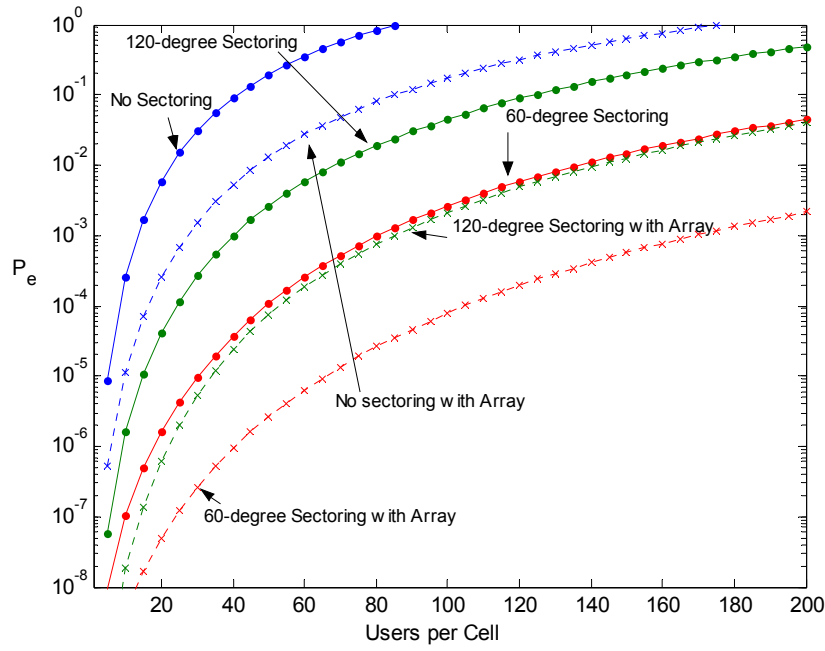
Figure 5.18   System Enhancement with −1 Degree of Orientation Offset in the Worst-

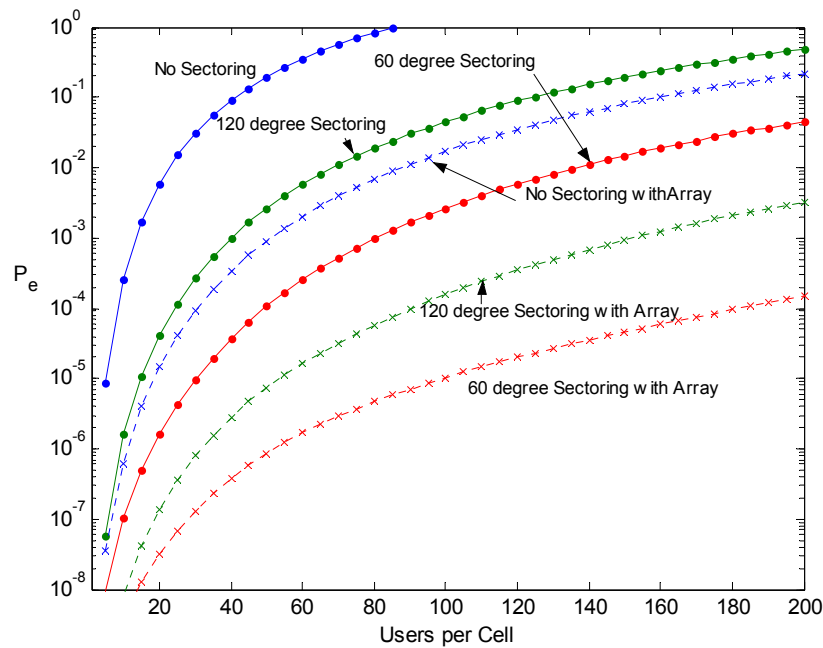Worst Case for a 3-Element Array (σ$_{dB}$=7, *Rcc*= ½, *v*=8)
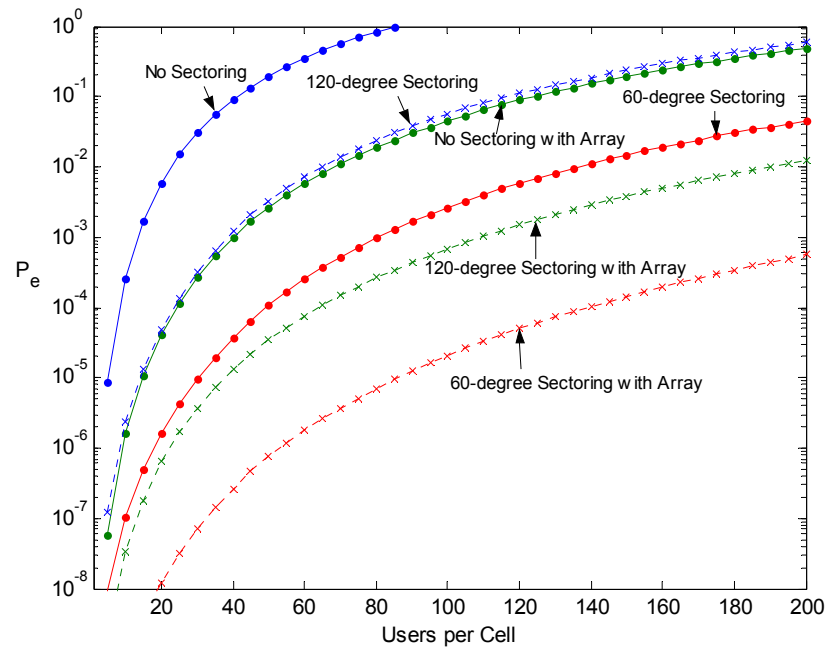
Figure 5.19   System Enhancement with +1 Degree of Orientation Offset in the Worst-

Worst Case for a 4-Element Array (σ$_{dB}$=7, *Rcc*= ½, *v*=8)

We have demonstrated that with 2- and 3-element linear arrays, we can improve the maximum number of active users per cell at SNR per bit of 15 dB with a shadowing of σ_{dB} =7 dB to 600% and 900% respectively, higher than a system without the linear array. Different sectorings were also performed on the system, which can dramatically improve the system's capacity. Our analyses in this chapter assumed that the antenna perform identically at all frequencies. This may be true for narrow–band channel. For a wide-band channel, we would need the application of tapped-delay line (transversal filter) be employed to equalize the frequency varying effect. Chapter VI presents the application and performance analysis of the tapped-delay line in our DS-CDMA mobile communication system.

VI   PERFORMANCE ANALYSIS OF WIDEBAND ADAPTIVE ANTENNA SYSTEM

Earlier we assumed that our DS-CDMA system under analysis is a narrowband system. The presence of a single complex adaptive weight in each element channel of an adaptive array is sufficient for processing narrowband signals. However, the processing of broadband signals, such as the forward channel of a 3G DS-CDMA network, requires that tapped-delay line (transversal filter) be employed in each element channel. In a practical implementation, every channel is slightly different electrically, which leads to channel mismatching. This mismatch could cause significant differences in frequency response characteristics from channel to channel and may severely degrade the array performance. Figure 6.1 shows the block diagram of the K-element antenna with L-tapped-delay line system
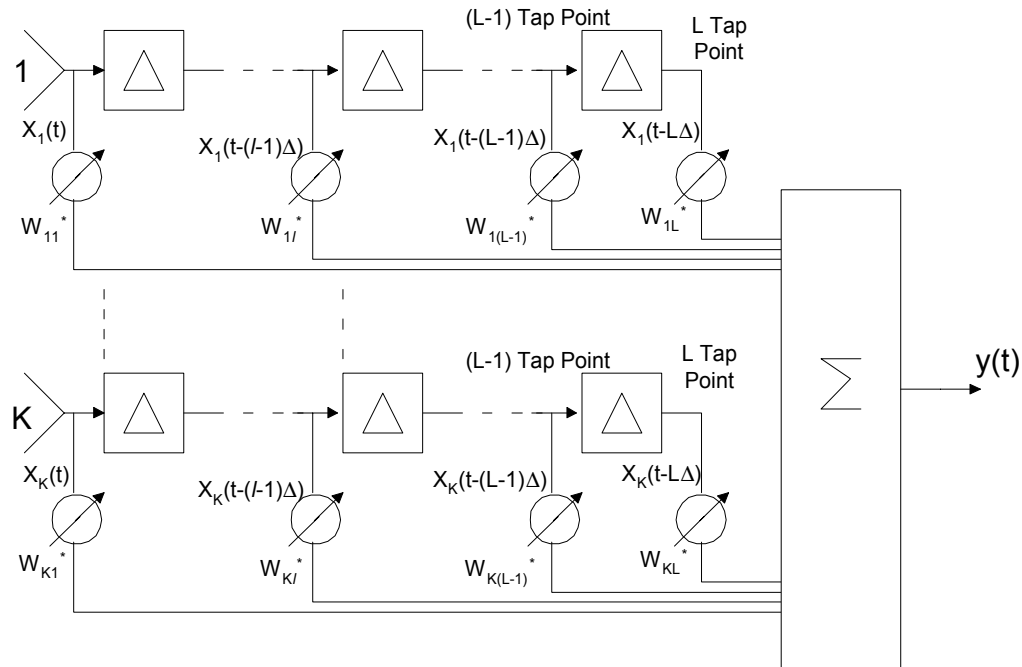

Figure 6.1   Wideband K-Element Array with an L-Tapped-Delay Line

The output of array, *y(t),* is defined as:

$$y(t) = \sum_{l=1}^{L} \sum_{k=1}^{K} w_{kl}^* x_k(t - (l-1)\Delta) = W^* X(t) \qquad (4.18)$$

where

$$W = \begin{bmatrix} W^{(1)} \\ W^{(2)} \\ \cdot \\ \cdot \\ W^{(L)} \end{bmatrix}, \quad W^{(1)} = \begin{bmatrix} w_{11} \\ \cdot \\ \cdot \\ \cdot \\ w_{K1} \end{bmatrix}, \quad \dots \quad W^{(L)} = \begin{bmatrix} w_{1L} \\ \cdot \\ \cdot \\ \cdot \\ w_{KL} \end{bmatrix}$$

.

$$X(t) = \begin{bmatrix} X^{(1)}(t) \\ X^{(2)}(t) \\ \cdot \\ \cdot \\ X^{(L)}(t) \end{bmatrix}, \quad X^{(1)}(t) = \begin{bmatrix} x_1(t) \\ \cdot \\ \cdot \\ \cdot \\ x_K(t) \end{bmatrix}, X^{(2)}(t) = \begin{bmatrix} x_1(t-\Delta) \\ \cdot \\ \cdot \\ \cdot \\ x_K(t-\Delta) \end{bmatrix}, \dots \dots X^{(L)}(t) = \begin{bmatrix} x_1(t-(L-1)\Delta) \\ \cdot \\ \cdot \\ X_K(t-(L-1)\Delta) \end{bmatrix}$$

The transfer function *H(f)* can be defined by taking the Fourier transform of the above *y(t)*.

$$H(f) = \frac{Y(f)}{X(f)} = \sum_{l=1}^{L} \sum_{k=1}^{K} w_{kl}^* e^{i2\pi f[(k-1)\tau + (l-1)\Delta]} \qquad (4.19)$$

where

$$\tau = \frac{\delta \sin \theta}{v}$$

and Δ is the inter-tap delay spacing (in our analysis using 2- and 3-tapped-delay line, $\Delta = \lambda_o/4$), *v* is the speed of light and δ is the linear antenna array separation, and θ is the direction of arrival of the signal (desired or interference).

We see that an array system with tapped-delay line may be able to equalize the broadband signal, but we need a more complex algorithm and more computational power to determine an optimized set of weights. In the case of a 3-element linear array, we need

to obtain 6 weight values whereas a 3-element, 3-tapped delay line system requires 18 weight values. We must note that the amount of time to determine a set of optimized weights increases significantly with the number of taps, which is critical for implementation. Hence the number of taps for a tapped-delay line implementation should be minimized to conserve electrical power and evaluation time.

We now apply tapped-delay line (transversal filter) processing to each antenna element channel to allow frequency-dependent amplitude and phase adjustments for the broadband signals. The use of a tapped-delay line thereby provides the capability of equalizing the frequency varying effect on the antenna array when the latter is receiving a broadband signal. The performance of a DS-CDMA cellular system with a mobile-terminal equipped with a linear array tapped-delay line was analyzed and performed.

We perform optimization by minimizing the ISR at the center nominal frequency of the signals. The angle of arrival for the desired (SBS) signal and interference were assumed to be known and is used to determine the optimized complex weight values for the tapped-delay line. Figure 6.2 and Figure 6.3 show the optimized transfer functions *H(f)* in (4.19) of a 2-element linear array with a 2- and 3-tapped delay line at 4% bandwidth of the nominal center frequency. We can see that the optimized desired signal base-station (SBS) remains flat over the 4% bandwidth width while the transfer functions of the interference base-station (IBS) may fluctuate significantly over the same bandwidth. Although at the nominal center frequency, we may achieve excellent ISR suppression greater than –70 dB (3-tap case with IBS1 as the main suppressed interferer), at the lower 4% band-edge we can only achieve about –16 dB of ISR.

Figure 6.2   Desired Signal (SBS) and Interference Signal (IBS) Transfer Functions of
a 2-Element Array with a 2-Tapped-Delay Line System and 4% Bandwidth

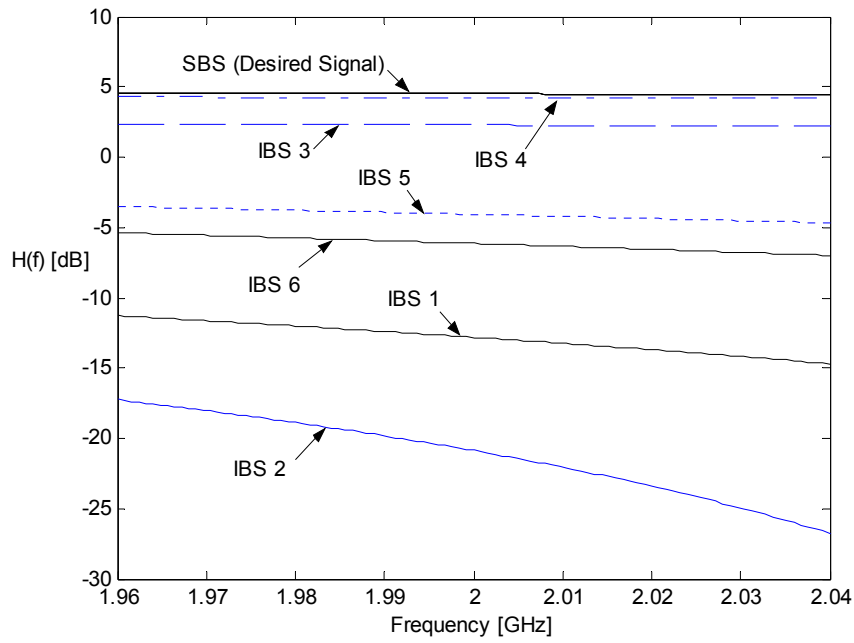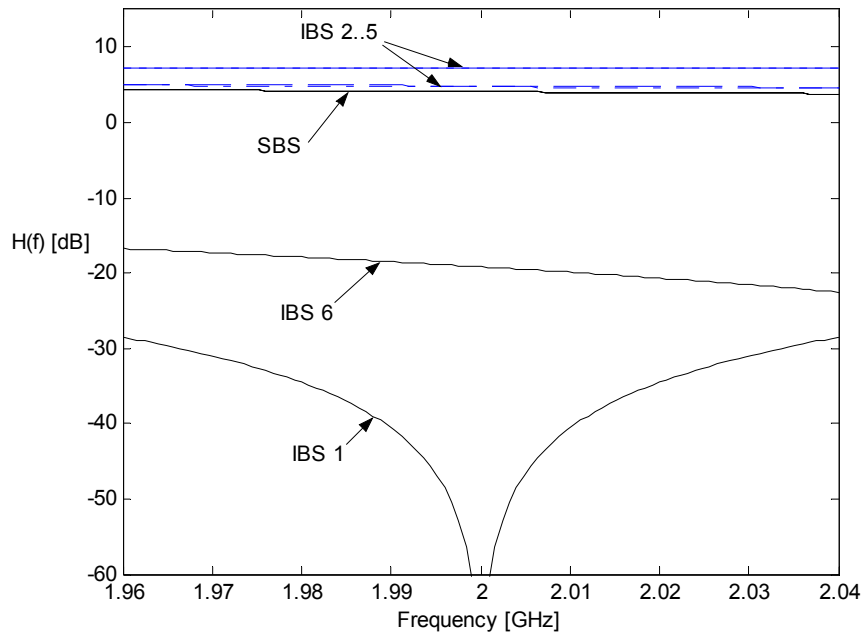

Figure 6.3   Desired Signal (SBS) and Interference Signal (IBS) Transfer Functions of
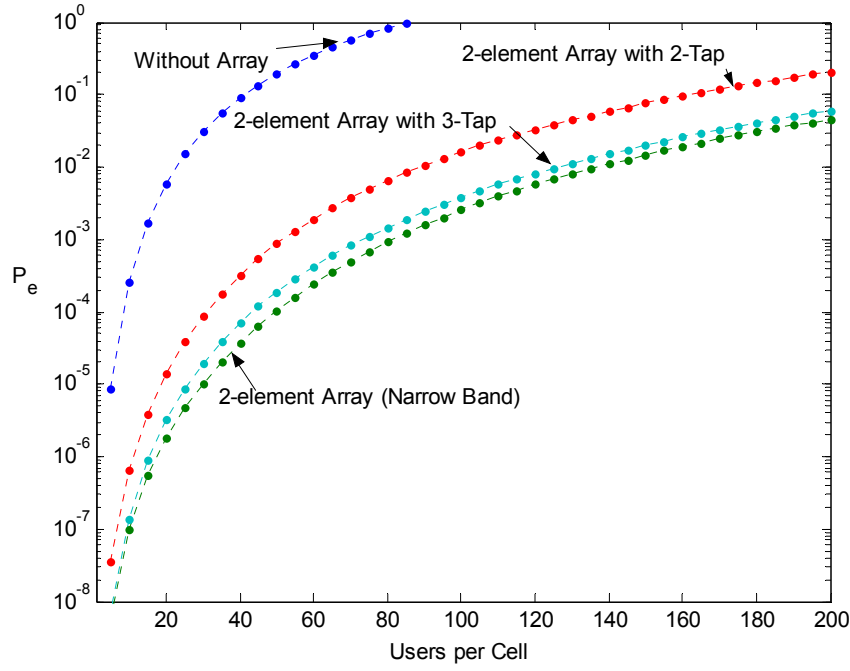a 2-Element Array with a 3-Tapped-Delay Line System and 4% Bandwidth

Figure 6.4   Performance Comparison Using a 2-Element Array with a 2- and 3-Tap-Delay Line for Broadband Signal (σ_{dB}=7,Rcc= ½, v=8) with 4% Bandwidth and No Sectoring

In order to evaluate the wideband system performance, we have adopted a more conservative approach by using the poorest result of the optimized transfer function for comparison. We first determined the poorest path-loss ratio (PLR) across the 4% bandwidth. In this, both the 2- and 3-tapped-delay line cases, the poorest performance point is found at the lowest frequency band-edge. We then use this PLR and apply it in the forward channel model by performing a Monte Carlo simulation similar to the narrowband case. Figure 6.4 shows the most conservative system capacity of a 2-element linear array with a 2- and 3-tapped-delay line system. At a BER of 10^{-3}, we can achieve a system capacity of 50 and 73 simultaneous active users respectively. These figures are 375% and 650% of a system without any smart antenna with a worst-case capacity of 13 active users.

However, if we compared the performance with the narrow band BW case, which has a system capacity of 80 active users, a 3-tapped-delay line performs similarly. This

demonstrates that if we could obtain a set of optimized weights for the tapped-delay line to equalize the broadband signal effectively, we could achieve a similar performance level as those in the narrow-band adaptive antenna system. As the complexity to determine the optimized weights of the adaptive tapped-delay line system increases exponentially with the number of taps used, in the case of the 2-element array, a 3-tapped-delay line may be sufficient to equalize the broadband signal while effectively suppressing the interference.

We repeat the process to obtain the optimum transfer functions for the 3-element array system with 2- and 3-tapped-delay line, as in Figures 6.5 and 6.6. In this 3-element array system, we determine the most conservative PLR is at the lowest frequency band-edge for a 2-tap case and at the highest frequency band-edge for a 3-tap case. Both PLR computed in this case are fairly close to each other. Figure 6.7 illustrates the system performance. We see that both 2- and 3-tap systems have similar performance, as their optimized path-loss ratios are only slightly different in magnitude. We can also see that both broadband cases outperform the narrowband case significantly (>200 active users). In the broadband 3-element antenna case, a 2-tapped-delay line should suffice to equalize the signal while providing superior system performance over the narrowband system.

In this chapter, we have evaluated the performance of a tapped-delay line application in a DS-CDMA mobile communication system. We are able to equalize the frequency varying effect of the broadband signal using tapped-delay-line. In a 2-element linear-array system, 3 taps would be sufficient to equalize the broadband signal while providing a similar performance level of a narrowband adaptive-array system. In the case of a 3-element linear-array system, 2 taps would suffice.

Figure 6.5   Desired Signal (SBS) and Interference Signal (IBS) Transfer Functions of
a 3-Element Array with a 2-Tapped-Delay Line System and 4% Bandwidth

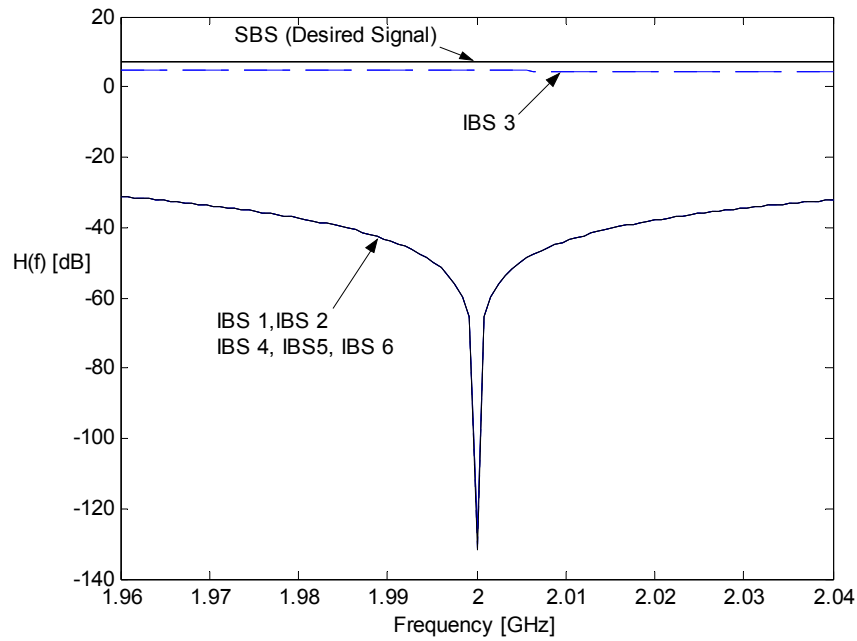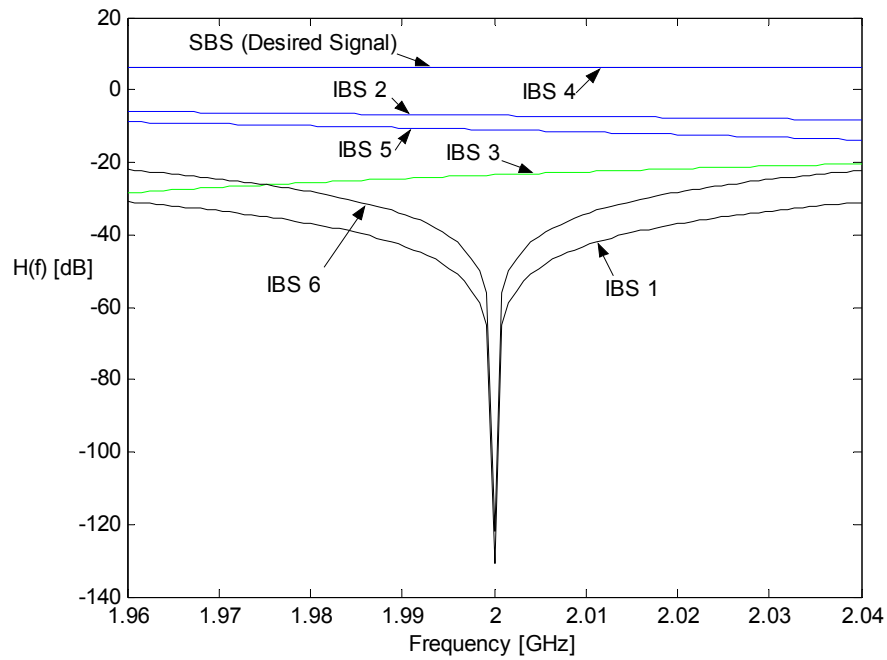

Figure 6.6   Desired Signal (SBS) and Interference Signal (IBS) Transfer Functions of
a 3-Element Array with a 3-Tapped-Delay Line System and 4% Bandwidth
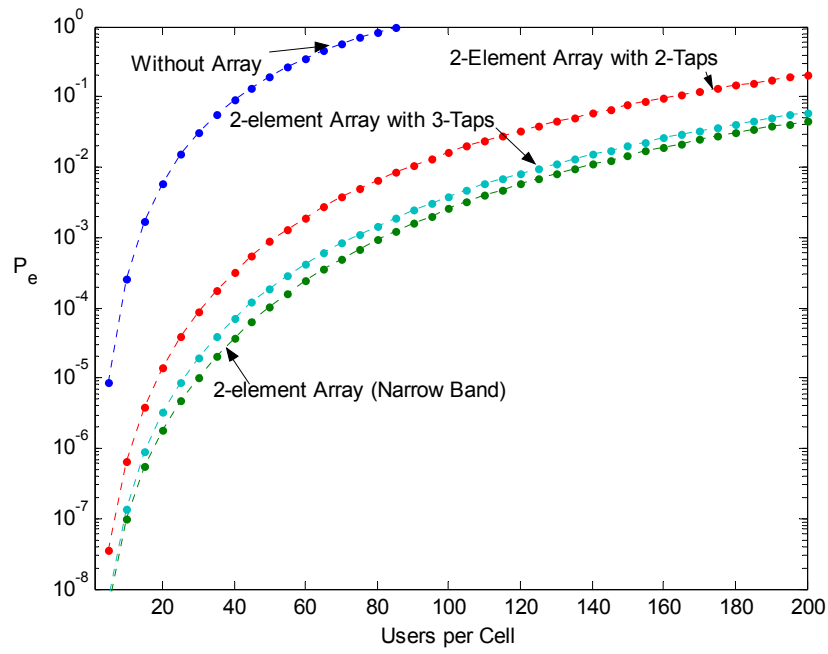
Figure 6.7   Performance Comparison Using a 3-Element Array with a 2- and 3-Tapped-Delay Line for Broadband Signal (σ_{dB}=7, *Rcc*= ½, *v*=8) with 4% Bandwidth and No Sectoring

VII   CONCLUSIONS AND FUTURE WORK

A.   CONCLUSIONS

In this thesis, we have applied an adaptive linear array at the mobile user terminal for a wideband DS-CDMA mobile communication system. A performance analysis was performed with a focus on the forward channel of the DS-CDMA system in a log-normal shadowing and Rayleigh slow flat-fading environment. The application of the adaptive linear antenna array compounded the problem of obtaining a representative system performance boundary because the mobile terminal can be randomly located anywhere in the cell and the antenna array is orientation limited. Further, the performance of the array may also vary significantly with a small change in orientation.

We used 2-, 3-, and 4-element linear arrays to evaluate the overall system's performance. Four performance boundaries (BB, WB, WW, BW) were established for each number of the linear arrays to compare and to evaluate the system's performance. These boundaries were reviewed and we determined that for a worst-case performance comparison, the WB case would be the tightest performance boundary for an array that can be orientated 360 degrees. In the case of a 2- or 3-element array system, the number of active users per cell that can be supported at SNR per bit of 15 dB with a shadowing of σ_{dB} =7 dB is 600% and 900%, respectively, higher than a system without the linear array. Different sectorings were also performed on the system, which can dramatically improve the system's capacity.

The application of the adaptive array has allowed the DS-CDMA system to perform better because of its superior interference suppression and this allows it to tolerate other constraining factors, such as higher fade depth.

To illustrate a practical implementation with ±5 degree freedom, when the array cannot orientate 360 degrees freely, all 3 different element array systems can still assure a system capacity enhancement of between 200% to 400% over the worst-case system

capacity for one that does not use any array. The adaptive array system has also demonstrated its versatility in providing a dramatic array performance enhancement with a small change of array orientation.

The performance of the adaptive-array system for a broadband signal is also evaluated with the use of a tapped-delay line. It has been demonstrated that the optimization process has been extremely computationally expensive and hence minimum taps should be used for practical consideration. The result obtained also illustrated that, in general, for a 2-element linear-array system, 3 taps would be sufficient to equalize the broadband signal while providing a similar performance level of a narrowband adaptive-array system. In the case of a 3-element linear-array system, 2 taps would suffice.

B.   FUTURE WORK

As a future research subject, the DS-CDMA system performance analysis with an adaptive array in a Rayleigh fading and log-normal slow fading environment can be extended to a system with a circular array antenna. two-dimensional or even three-dimensional time and an angle-of-arrival geometric model can also be incorporated into the system's performance analysis.

LIST OF REFERENCES

[1] Y. Okumura, "Field Strength and Its Variability in VHF and UHF Land Mobile Radio Service," *Reviews of the Electrical Communications Laboratory (Japan)*, vol. 16, no. 9-10. pp. 825-873, September-October 1968.

[2] COST 231,"Urban Transmission Loss Models for Mobile Radio in the 900 and 1800 MHz bands(Rev. 2)," *COST 231 TD(90) 119 Rev. 2*, The Hague, September 1991.

[3] John G. Proakis, *Digital Communications*, 4th Edition, McGraw Hill, 2001.

[4] J.E Tighe, "Modeling and Analysis of Cellular CDMA Forward Channel," PhD Dissertation, Naval Postgraduate School, Monterey, CA, March 2001.

[5] Ramakrishna Janaswamy, *Radiowave Propagation and Smart Antennas for Wireless Communications*, Kluwer Academic 2001.

[6] Ayman F. Naguib "Adaptive Antennas for CDMA Wireless Networks," PhD Dissertation, Stanford University, CA, August 1996.

[7] Theodore S. Rappaport, *Wireless Communications Principle and Practice*, 2nd Edition, Prentice Hall, 2002.

[8] Robert A. Monzingo and Thomas W. Miller, *Introduction to Adaptive Arrays,* New York:Wiley, 1980.

[9] Kaiser Tan B.K., "Performance Analysis of Adaptive Antenna with Coding and RAKE Receiver," MSc Dissertation, Naval Postgraduate School, Monterey, CA, March 2002.

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